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Are we entering the Trigeneration?

The Feasibility of Combined Cooling, Heating and Power in the United Kingdom

By

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Abstract

Trigeneration or combined cooling, heating and power, is the decentralised generation of electricity for use in one or more sites. The waste heat from this process is used to heat buildings, generate domestic hot water or provide cooling via an absorption chiller.

This document assesses the feasibility of Trigeneration in the UK, in terms of; the ability for delivery of heating, cooling and electrical energy in an efficient and cost effective manner; the issues surrounding its design and installation; and ultimately whether it can make a significant reduction in carbon emissions in the United Kingdom.

Calculation results show the carbon emissions associated with generating electricity, heating and cooling energy in a Trigeneration facility can be as much as 34% less, than those emitted from conventional boiler and chiller plant installations and that a payback period of 6 years is possible. The study shows that to maximise financial and environmental potential: the heat to power ratio of CCHP must be low, preferably 1:1; the heating to cooling output ratio should ideally be 3:1 or greater; and heat utilisation should exceed 90%. If 50% of UK electricity could be delivered from highly efficient CCHP installations, carbon emission savings for delivered UK gas and electrical energy of up to 10.5% could be realised.

Trigeneration is feasible for mass implementation within the UK and we are likely to see an increase in the number of Trigeneration facilities because of local government decentralised energy targets and the relatively onerous carbon emissions target of the Building Regulations.

Despite the clear benefits of CCHP, it is difficult to predict whether we will move our energy needs towards a Trigeneration solution. There are many hindrances to its introduction including the high installation cost, disturbance associated with installing CCHP facilities and heating and cooling networks and whether consumers would be willing to abandon their own boilers and chillers and connect to local networks.

An alternative solution to reduce UK carbon emissions attributed to delivered energy, with fewer disturbances to the utilities networks, is to replace the 66 existing inefficient fossil fuelled power stations, with modern efficient combined cycle gas turbine power stations. As aging boiler and chiller plant is refurbished, it should also be replaced with modern highly efficient conventional equivalents. The long term result of this would be a 6% greater carbon emission reduction, than is envisaged possible with mass implementation of Trigeneration.

For this reason, this study shows widespread installation of CCHP is not the best means currently available to lower carbon emissions attributed to energy generation and assist in meeting the UK's 2050 target to reduce emissions by 60%. Trigeneration is, however, a beneficial and feasible short term alternative to reduce the UK's impact on Global Warming.

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Lastly the author would like to thank his family, flat mates and girlfriend for their continued support over the past five months, without which, he surely would have gone insane.

I, Ashley Stone, confirm that the work presented in this study is my own. Where information has been derived from other sources, I confirm that it has been referenced.

Glossary of Terms

Absorption Chiller	A heat driven chiller used for the generation of chilled water for cooling purposes.
Approved Document L	A section of the UK Building Regulations which is concerned with the conservation of fuel and power in buildings.
Carbon Emissions	The carbon dioxide released in the burning of coal, gas and oil to generate electricity or heat.
Carbon Emissions Factor	Carbon dioxide emissions per unit of energy, usually expressed as Kg CO_2 / kWh or Tonnes CO_2 / GWh.
CHP	Combined Heating and Power, the decentralised generation of electricity for use in one or more sites. The waste heat from this process is used to heat buildings and generate domestic hot water.
CCGT Power Station	A centralised Combined Cycle Gas Turbine power station.
CCHP	Combined Cooling, Heating and Power, see Trigeneration.
CO_2	Carbon dioxide.
Conventional Boiler	A gas-fired condensing boiler, used to generate hot water for heating purposes.
Conventional Chiller	A mechanical vapour compression chiller fuelled by electricity, used to generate chilled water for cooling purposes.
Grid Supply Electricity	Delivered electrical energy provided by a centralised power station.
GWh	A measure of energy consumption equivalent to the use of one Gigawatt in one hour.
GWP	Global Warming Potential, a measure of the total energy absorbed by 1 kg of released gas over a fixed period of time, relative to CO_2.
Heat to Power Ratio	The amount of useful heating output relative to useful electrical energy output from a CHP engine, expressed as a ratio.
Heating to Cooling Ratio	The quantity of heat output from a CHP engine used directly for heating purposes, relative to that used to generate cooling energy in an absorption chiller, expressed as a ratio.
KWh	A measure of energy consumption equivalent to the use of one Kilowatt in one hour.
MWh	A measure of energy consumption equivalent to the use of one Megawatt in one hour.
Payback Period	The time estimated to be required for the financial savings stemming from a capital investment to equal the additional sum invested.
Trigeneration	Trigeneration or CCHP is the decentralised generation of electricity for use in one or more sites. The waste heat from this process is used to heat buildings, generate domestic hot water or provide cooling via an absorption chiller.
Whole Life Costing	The capital, installation, running and maintenance costs of an item, over its service life.

1 Introduction

1.1 The Carbon Emissions Problem

Since the beginning of the industrial revolution 250 years ago, an exponential increase in carbon emissions has resulted in the average worldwide carbon dioxide concentration level growing from 280ppm to 380ppm (National Oceanic and Atmospheric Administration, 2007). This growth has mainly been attributed to increased burning of fossil fuels, to provide more energy for the rising global population and for the additional energy consumed per person, resulting from improvements to quality of life.

We are now beginning to suffer the effects of this long term polluting of our environment, through elevated global temperatures, increased rainfall, flooding and rising sea levels. These climatic changes threaten our global environment and unless mitigated are believed to result in large areas of the world becoming uninhabitable as; low-lying land disappears below sea level; and ambient temperatures soar to uncomfortably high levels elsewhere.

In parallel to this, easily accessible oil and gas sources are continuing to decline and are generally concentrated in politically unstable regions, resulting in reduced fuel security. Oil and gas prices have risen in response, resulting in severe effects on economies worldwide. As a result between 2004 and 2006 output from coal power stations in the UK increased by 14%, whilst output from less carbon intensive combined cycle gas power stations fell by 9% (BERR, 2007).

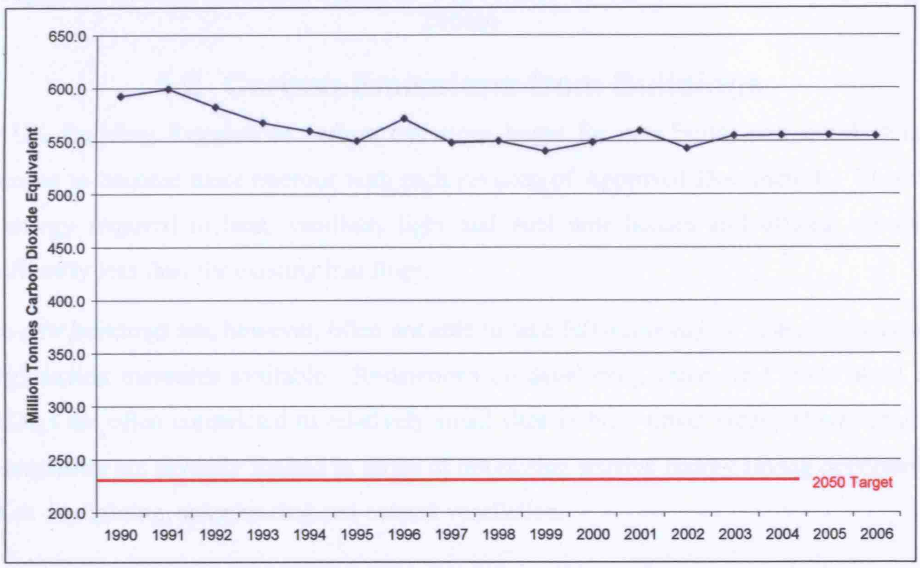


Figure 1 : UK Carbon Dioxide Emissions 1990-2006 (AEA Energy & Environment (AEA), 2008a)

In 2007 the UK government set an ambitious target to decrease the UK's carbon emissions by 60% of 1990 levels by 2050, in order to reduce the UK's impact on climate change and reliance on foreign fuel imports. A general switch from coal to gas power stations in the 1990s resulted in a decline in carbon emissions of 8.8% by 1999. Since 1999 levels have risen slightly as transport, computing, lighting and air conditioning energy usage has grown and output from more cost effective but more carbon intensive coal power stations has increased, see Figure 1.

Of total annual carbon emissions in the UK, 39% can be attributed to the energy supply sector, 21% to road transportation, 17% to the business sector, 15% to the residential sector and 10% to other sectors, see Figure 2. Significant carbon emission reductions in all these sectors, and in particular the energy supply sector, will be required for the government to meet its emissions reduction target.

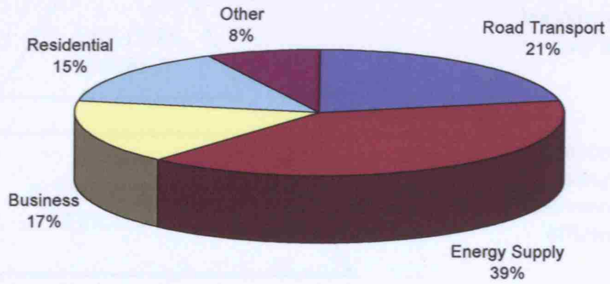


Figure 2: Carbon emissions by Sector Type (AEA Energy & Environment (AEA), 2006b)

1.2 Carbon Emissions from Buildings

The UK Building Regulations carbon emissions target for new builds and refurbishments continues to become more onerous with each revision of Approved Document L. Therefore the energy required to heat, ventilate, light and cool new houses and offices, should be significantly less than for existing buildings.

Even new buildings are, however, often not able to take full advantage of many of the passive energy saving measures available. Restrictions on developing green field site's mean new buildings are often constricted to relatively small sites in busy urban areas, where architects and engineers are severely limited in terms of optimising passive energy saving opportunities such as daylighting, solar heating and natural ventilation.

In London, the Mayor has devised an energy hierarchy to assist in lowering building energy. This states: firstly energy usage should be reduced; secondly energy should be supplied more efficiently; and finally renewable energy sources should be utilised (Stevenson et al, 2008). Energy usage in new buildings has been reduced through tougher requirements for building fabric performance, lighting efficiency and control systems; although increased air conditioning and computing has generally offset this. A renewable energy target for lowering carbon emissions attributed to building heating, cooling, ventilation and lighting energy in new buildings, has been set at a 20% carbon dioxide reduction through renewable energy sources (London Plan Policy 4A.7, 2008). The British Council for Offices state that on average new offices in London have achieved only a 7% reduction in carbon dioxide from renewable technologies due to the constraints urban environments impose (Irwin G., 2007).

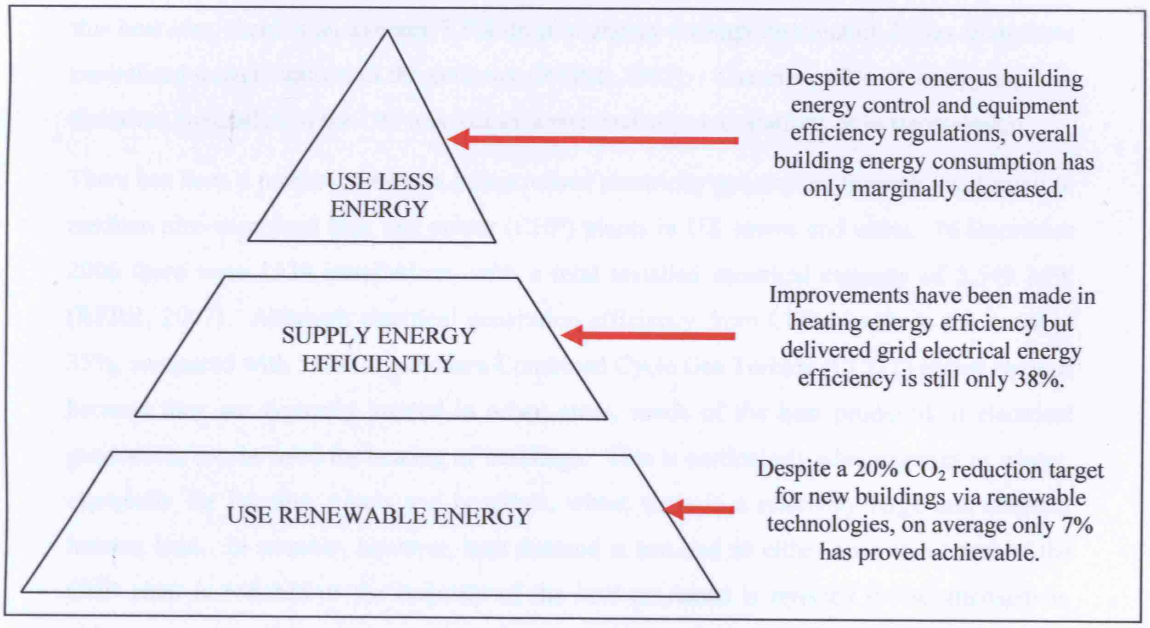


Figure 3: Progress With Regards to the Mayor of London's Energy Hierarchy to Tackle Carbon Emissions

To date, reducing energy usage and incorporating renewable energy sources has proven to be difficult. As the energy supply sector is responsible for 39% of carbon emissions, it is key that methods of increasing efficiency of delivered electricity, heating and cooling energy in buildings, are implemented.

1.3 Delivered Electricity, Heating and Cooling

Consumed fuel by final end user, for all UK domestic and non-domestic uses, excluding petroleum, is 61% gas, 34% electricity and the remainder a mix of solid fuels and renewable sources (BERR, 2007). Improvements in building services technologies have resulted in high delivered heating and cooling efficiencies, with seasonal boiler efficiencies of over 96% and heat pump seasonal energy efficiency ratios of 5.5. However, the average efficiency of power stations in the UK in 2006 was only 41% (BERR, 2007).

The key reason for this poor efficiency is that electrical energy generation in the UK is mostly via gas or coal power stations, which produces a large quantity of heat. This heat is traditionally released into the atmosphere in large cooling towers because power stations are usually located too far from any buildings, where this heat could be utilised. In addition to this heat loss, there is an average 7.5% drop in energy through distribution losses from these centralised power stations to the end user (BERR, 2007). Therefore 62% of energy input in electrical generation in the UK was lost as waste heat at power stations or in transmission.

There has been a recent increase in decentralised electricity generation, through local small to medium size combined heat and power (CHP) plants in UK towns and cities. In December 2006 there were 1539 installations, with a total installed electrical capacity of 5,549 MW (BERR, 2007). Although electrical generation efficiency from CHP is only in the order of 35%, compared with 55% for a modern Combined Cycle Gas Turbine (CCGT) power stations because they are typically located in urban areas, much of the heat produced in electrical generation, can be used for heating of buildings. This is particularly advantageous in winter, especially for housing, hotels and hospitals, where there is a relatively large and constant heating load. In summer, however, heat demand is less and so either operation hours of the CHP plant is reduced or the majority of the heat produced is rejected to the atmosphere, reducing the net efficiency of the CHP plant.

A relatively recent solution has been to use this waste heat in summer to drive an absorption chiller, to generate cooling for buildings. This is known as combined cooling, heating and power (CCHP) or Trigeneration and installations in the UK include the Natural History Museum, University of Edinburgh and Citigen, a large district heating and cooling network in London. National planning policy now requires the consideration of CCHP as a carbon reduction option for all new major developments and many new planned sites, including those for the London 2012 Olympics, are intending to incorporate it.

There are still only a small number of Trigeneration installations across the UK and relatively little is known about the success of these schemes and their feasibility for use elsewhere. The actual environmental benefits have also been questioned, with claims that because of the poor coefficient of performance of absorption chillers, CCHP is likely to be more carbon intensive than modern conventional plant (Thronger J., 2007).

1.4 The Task

This document has been complied to assess the feasibility of Trigeneration in the UK, in terms of:

- The delivery of heating, cooling and electrical energy in an efficient and cost effective manner;
- The issues surrounding the design and installation of Trigeneration and ease of refurbishment of existing conventional plant;
- Whether Trigeneration can make a significant reduction in carbon emissions compared with conventional grid electrical supply, boiler and chiller plant.

Although there are existing guides and studies which evaluate combined heat and power, such as Good Practice Guide 388 (Action Energy, 2004) and others such as Good Practice Guide 256 (ETSU and ENVIROS, 2001) which evaluate absorption cooling, there are no known studies focusing on the feasibility of Trigeneration within the UK. It is hoped the results of this study will assist consultants, planners and clients in assessing whether Trigeneration is feasible for existing and future developments and to provide guidance on how to size and operate a facility to minimise carbon emissions.

The processes involved in Trigeneration are discussed in the following chapter.

2 What is Trigeneration

This Chapter outlines how electricity, heating and cooling is generated through a combined cooling, heating and power plant (CCHP), through examining the processes involved in combined heat and power and absorption cooling. Figure 4 summarises the basic principle of CCHP, also called Trigeneration.

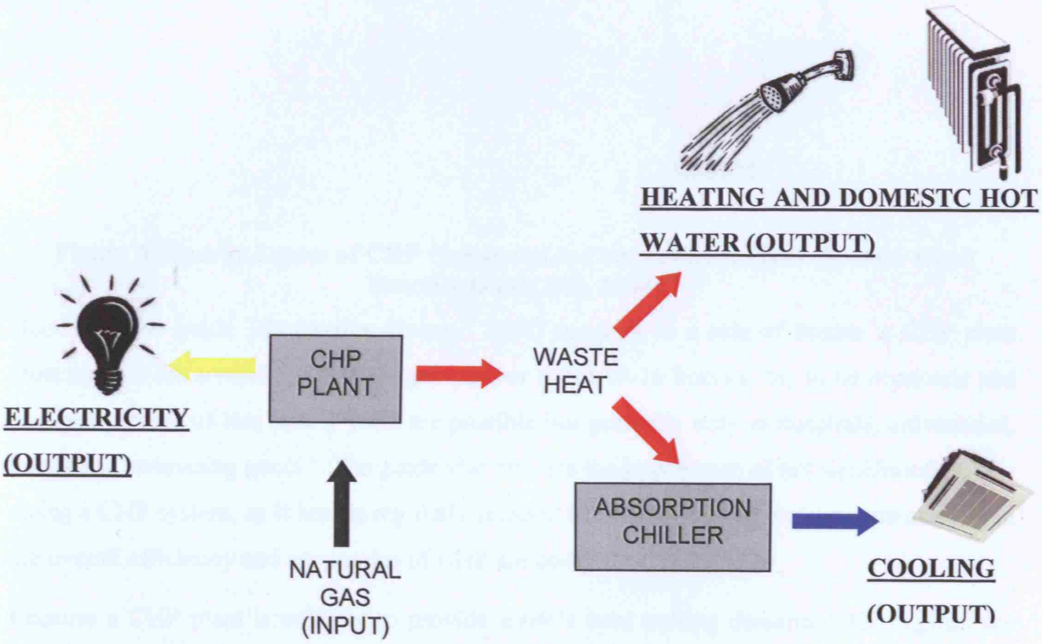


Figure 4: Trigeneration Schematic

2.1 Combined Heat and Power (CHP)

Combined heat and power is the decentralised generation of electricity for use in one or more adjacent sites. The waste heat of this process is used to heat buildings or to generate domestic hot water. The potential environmental benefits of this are high, with estimated losses in CHP as low as 20% (15% flue losses and 5% radiations losses), compared with approximate combined losses of 44% for grid supplied electricity and conventional gas condensing boilers, for equivalent heat and power loads, see Figure 5. Thus the required primary energy to meet a site's electricity and heating demand can be significantly reduced. The environmental benefits are discussed in more detail in Chapter 5.

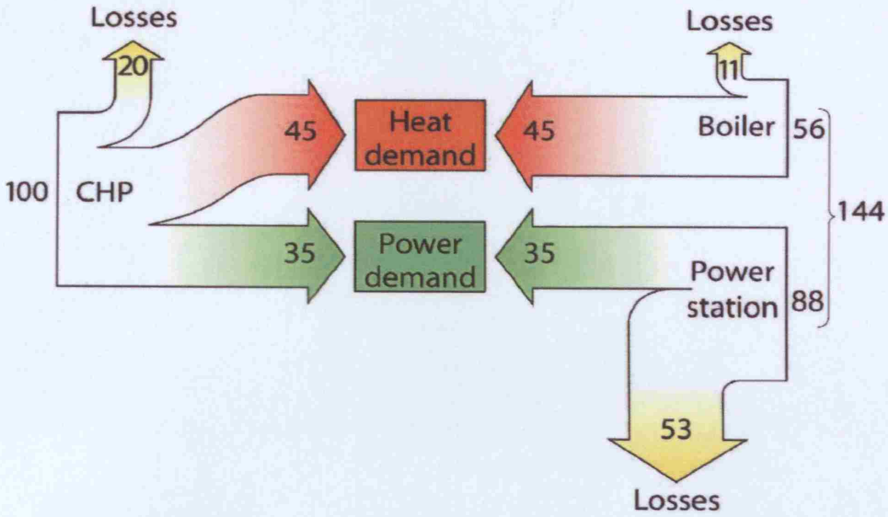


Figure 5: Energy Losses of CHP Compared to Conventional Plant (Source: Good Practice Guide 388, 2004)

Good Practice guide 388 (Action Energy, 2004) suggests as a rule of thumb 'a CHP plant must operate for around 5,000 hours per year or about 14-16 hours a day to be economic and payback periods of less than 5 years are possible but generally only in hospitals, universities, hotels and swimming pools.' The guide also stresses the importance of not significantly over-sizing a CHP system, as if heat is regularly rejected to atmosphere rather than consumed, then the overall efficiency and economics of CHP are poor.

Because a CHP plant is unlikely to provide a site's total heating demand, CHP engines are typically installed in parallel with conventional gas condensing boilers, with the CHP plant acting as the lead boiler, to maximise its running time. It is also possible to incorporate hot water thermal storage to increase the running hours of the CHP plant, through load levelling.

Most CHP systems are sized on base heating load and so it is possible electrical demand may exceed site demand. In these instances the installation can be configured to export electricity to the grid. Under normal operation, however, grid electricity will be required to supplement the output from the CHP plant to meet a site's electrical demand.

There are three main types of CHP system in operation:

2.1.1 Reciprocating Engine CHP

The majority of small scale CHP installations are packaged gas reciprocating engines, see Figure 6, where an engine drives an electrical generator and heat is reclaimed from exhaust gases and the cooling system, for heating purposes.

The hot water flow temperature is typically up to 95°C. The size of these units varies from 50kW to 800kW electrical output, with a heat to power ratio in the order of 1.5:1. Efficiency is as much as 90%, if coupled with a condensing heat exchanger and power output can be modulated over a wide range.

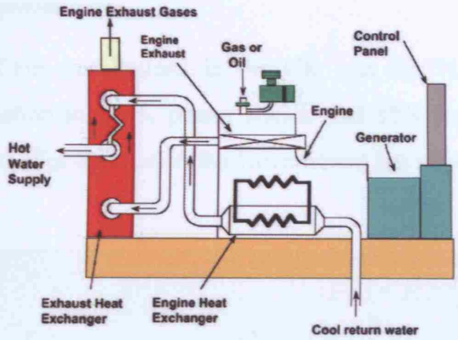


Figure 6: Small Scale CHP Engine (Source: Good Practice Guide 388 (2004))

2.1.2 Gas Turbine CHP

Gas Turbine CHP is used for larger installations with electrical output above 1 MW. Pressurised combustion gases drive an electrical generator and the high temperature exhaust gasses (above 450°C) are used as a source of energy for heating purposes. This arrangement would therefore provide high temperature heating for a building. The heat to power ratio is variable in this system (5:1 to 1.5:1) and hence electrical and heating output can better match demand. The efficiency is, however, less than for a reciprocating CHP plant, especially at low loads.

2.1.3 Micro Turbines

According to GPG 388 (Action Energy, 2004) Micro Turbine CHP plants come in a similar size range and performance to reciprocating engine CHP but they claim to have reduced maintenance costs, as there are fewer moving parts.

2.2 CHP Output in the United Kingdom

The Department for Business Enterprise and Regulatory Reform (BERR) collates data for CHP output and efficiency within the UK, see Table 1. Since the first schemes were introduced in 1977, electrical output has grown from 10,450 GWh to 27,973 GWh electrical in 2006 and there are now more than 1,500 installations. Although electrical output has risen by 156%, useful heat output has remained fairly constant at 55,000 GWh, see Figure 7. This is due to the desire to maximise electrical output from CHP, as electric grid unit price is very high in comparison with gas, plus any output above a site's demand can be sold to the grid at profit, whereas excessive heat is typically dumped reducing the efficiency of the plant. Thus newer schemes have tended to have lower heat to power ratios.

In 2006, the average efficiency of all of the CHP installations in the UK was 67.7%, compared with 41% for average electrical generation in a UK power station and 55% for generation from a modern CCGT gas power station. For this reason the Government has set a target of 10,000 MWe CHP capacity by 2010.

Year	Number of Schemes	Electrical Capacity	Heat capacity	Heat to Power Ratio	Fuel Input	Electrical Generation	Heat Generation	Overall Efficiency
		Mwe	MWth		GWh	GWh	GWh	%
1977		2,793				10,450		
1983		2,254				7,500		
1988		1,793				8,700		
1991	266	2,293	13,361	5.8	113,537	10,917	65,174	67
1993	996	2,893	14,442	4.12	101,650	14,171	58,418	71.4
1994	1,143	3,117	15,704	4.67	97,322	12,853	60,079	74.9
1995	1,224	3,355	15,698	3.85	106,515	14,778	56,833	67.2
1996	1,303	3,042	15,383	3.81	98,006	14,785	56,291	72.5
1997	1,325	3,205	15,027	3.46	97,897	15,702	54,335	71.5
1998	1,335	3,440	15,112	3.16	100,890	17,573	55,585	72.5
1999	1,361	3,670	14,645	2.81	100,564	19,108	53,762	72.5
2000	1,498	4,476	11,682	2.18	106,852	25,338	55,201	75.4
2001	1,527	4,479	11,692	2.61	109,931	21,327	55,737	70.1
2002	1,509	4,595	11,353	2.35	113,263	23,304	54,875	69
2003	1,509	4,524	11,015	2.3	113,676	24,015	55,286	69.8
2004	1,499	5,427	11,855	2.11	120,759	26,931	56,829	69.4
2005	1,542	5,571	11,590	1.96	125,347	28,938	56,839	68.4
2006	1,539	5,549	11,477	1.92	120,589	27,973	53,631	67.7
2010*		10,000						

Notes:
* - Government Target

Table 1 : CHP Installed Capacity 1977 to 2006 (BERR, 2007)

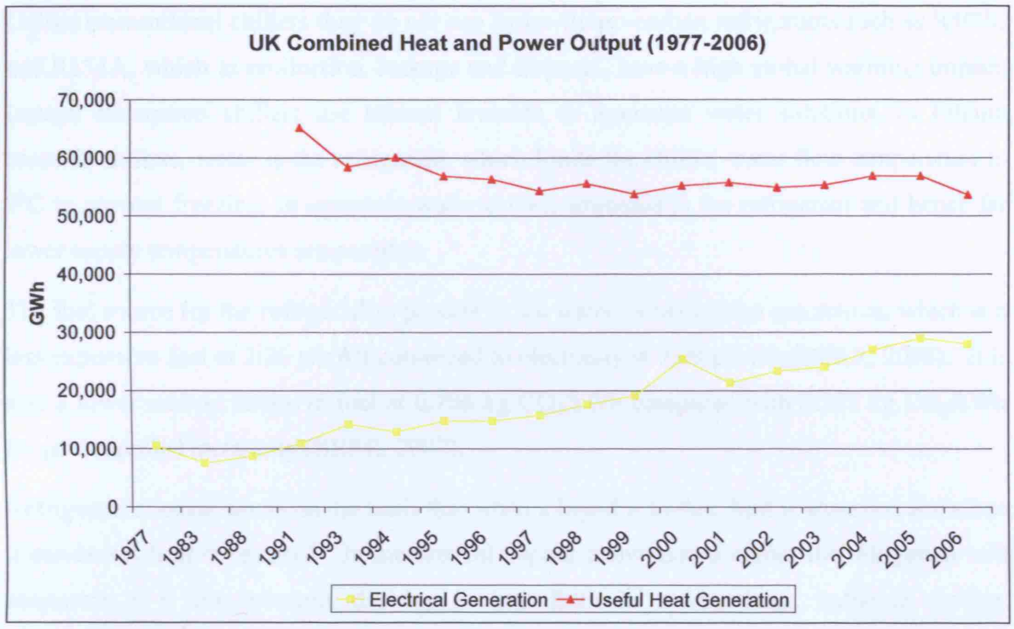
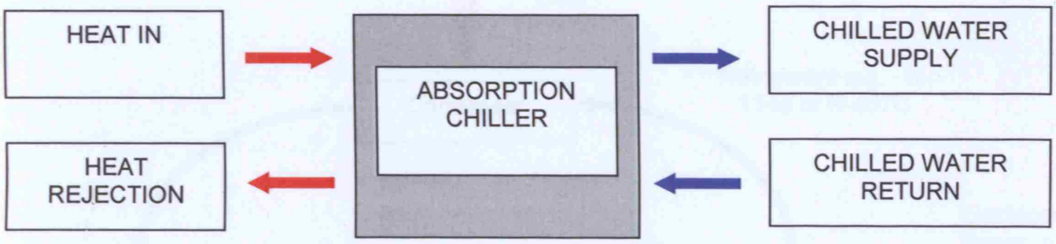


Figure 7: UK Combined Heat and Power Output (1977-2006) (BERR, 2007)

2.3 Absorption Cooling



Absorption cooling is the process of generating cooling energy from heat input, typically from a gas fired source. In 2001, there was in the region of 2,700 installed absorption chillers in the UK but only around 15 large units, i.e. with capacities in excess of 300kW, are sold in the UK each year (ETSU and ENVIROS, 2001). Absorption chillers tend to be used in place of mechanical vapour compression chillers, where there is a site with excessive heat rejection, say from a combined heat and power plant or where there is a site limit on electrical consumption.

Absorption chillers have a much lower coefficient of performance than conventional chillers, typically 0.7 compared to above 4 for conventional chillers but where there is a large heat source that would otherwise be wasted, they can be less carbon intensive than conventional chillers.

Unlike conventional chillers they do not use hydro-fluoro-carbon refrigerants such as R407C and R134A, which in production, leakage and disposal, have a high global warming impact. Instead absorption chillers use lithium bromide or ammonia water solutions. In lithium bromide chillers, water is the refrigerant, which limits the chilled water flow temperature to 5°C to prevent freezing, in ammonia water chiller, ammonia is the refrigerant and hence far lower supply temperatures are possible.

The fuel source for the refrigeration process is hot water, usually from gas source, which is a less expensive fuel at 2.26 p/kWh compared to electricity at 7.09 p/kWh (BERR, 2008). It is also a lower carbon intensive fuel at 0.206 kg CO_2/kWh compared with 0.521 kg CO_2/kWh for grid supplied electricity (BERR, 2007).

Refrigerant cooling works on the basis that when a liquid is boiled, heat is absorbed and when it condenses heat is released. In mechanical vapour compression chiller the refrigerant will evaporate at a low pressure, drawing in heat from its surroundings, inducing cooling. Electrically driven mechanical compressors then increase the refrigerant pressure, so that it condenses and rejects heat to the atmosphere or to the ground, see Figure **8**.

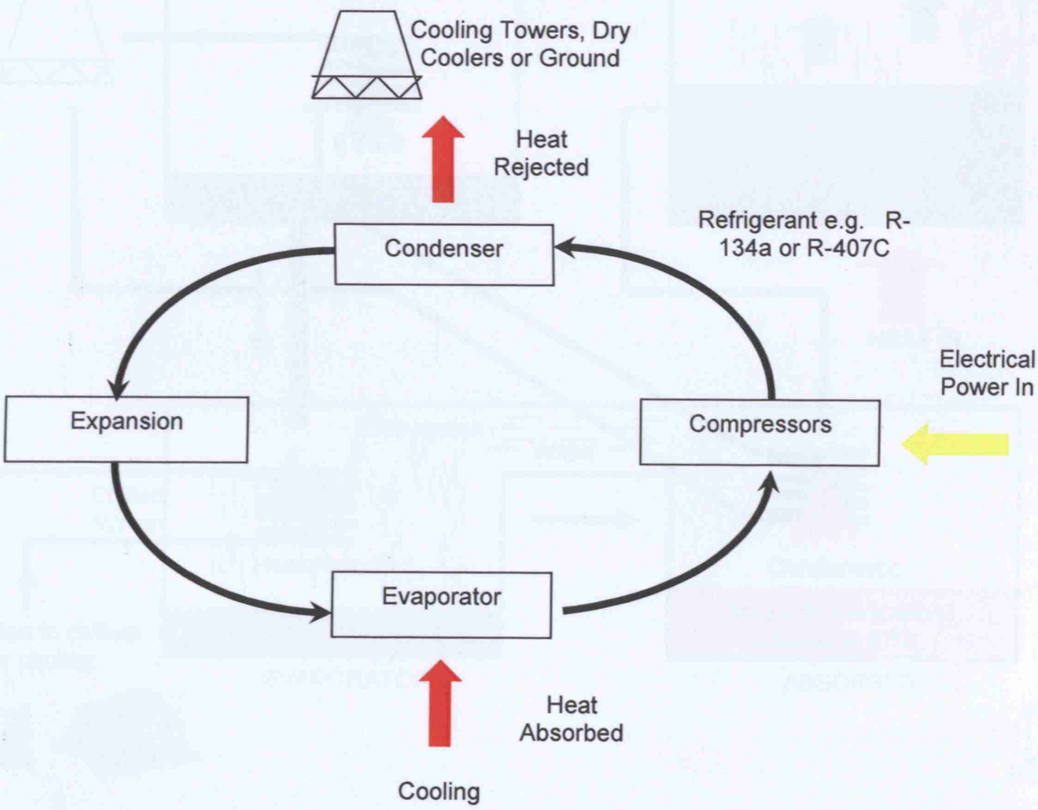


Figure 8: Mechanical Vapour Compression Cooling (Diagram adapted from Page 4 of Good Practice Guide 256, ETSU and ENVIROS, 2001)

In absorption cooling there are no compressors but instead a chemical absorber, generator and small pump. A lithium bromide or ammonia solution draws water vapour from the evaporator into the absorber diluting the solution. This "weakened" solution is then pumped at a slightly higher pressure to the generator, where heat is applied evaporating the refrigerant. The refrigerant then condenses and is recycled in the absorber, where heat is rejected, see Figure 9. This diagram is a representation of a single effect absorption chiller, note the heat exchanger between the generator and absorber is not shown for simplicity.

Double and triple effect absorption chillers, which recycle heat to improve efficiency, are available. These require a heat input above 140°C. Most reciprocating engine CHP plants generate heat at 85-90°C. For a Trigeneration plant, where waste heat from CHP will be used to fuel the absorption chiller, single effect chillers are most commonly used, see Figure 10.

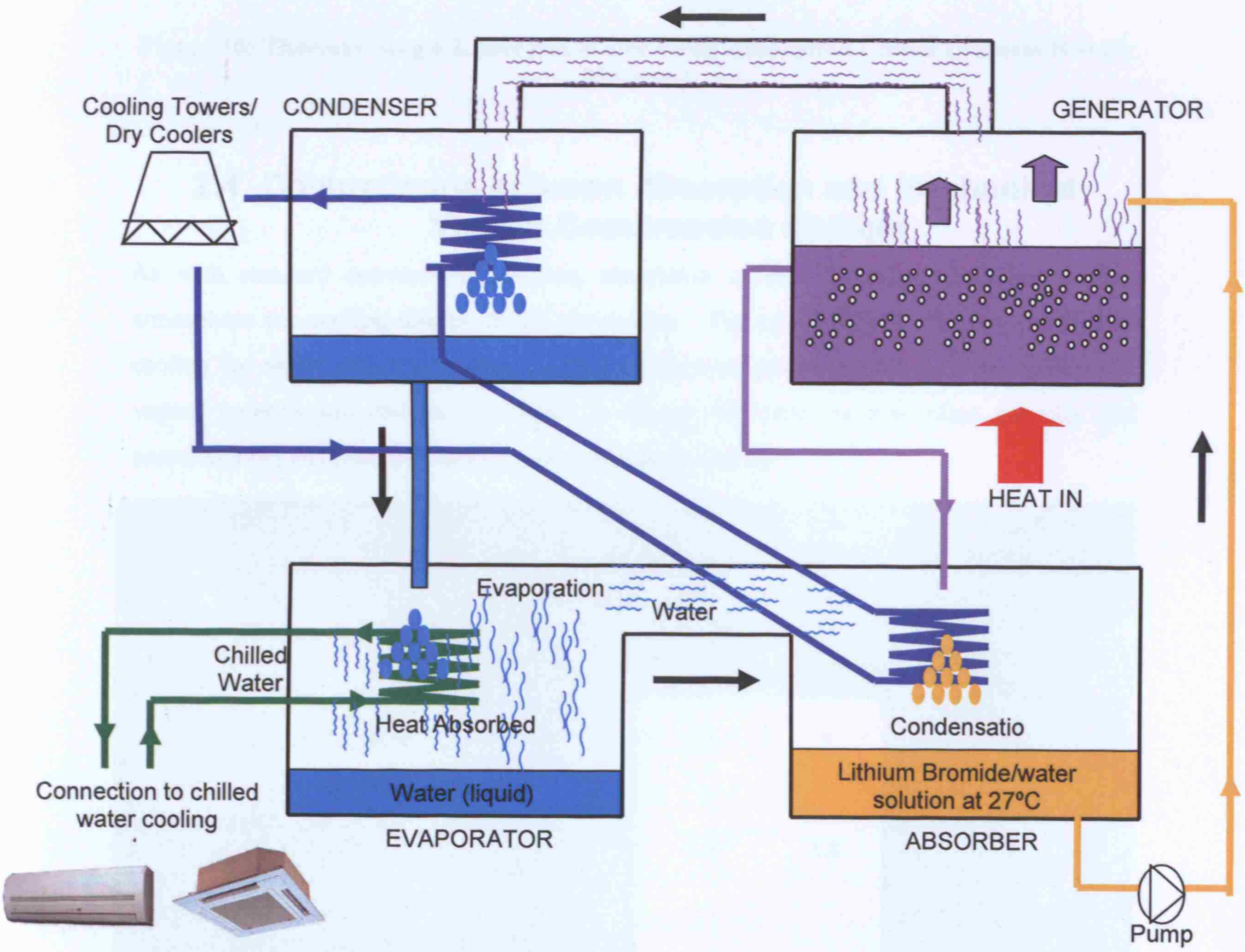


Figure 9: Simplified Diagram of Absorption Cooling (Adapted from Figure 4 of Trend and Application of Absorption Chiller, Chung B, 2007)

Figure 10: Thermax Single-Effect Hot Water Fired Absorption Chiller (Natural History Museum)

2.4 Comparisons between Absorption and Mechanical Vapour Compression Chillers

As with standard conventional chillers, absorption chillers typically reject heat to the atmosphere via cooling towers or dry air coolers. The required heat rejection per kW of cooling for single effect absorption chillers is however, nearly double than for mechanical vapour compression chillers, see Table 2. Hence, the heat rejection plant capacity and associated fan and pumping energy is approximately double.

	Lithium Bromide Absorption Chillers			Mechanical Vapour Compression Chiller
	Single Effect Steam or Hot Water	Double Effect Steam	Double Effect Gas Fired	Electric Reciprocating
Coefficient of Performance	0.68	1.2	1	>4
Heat Rejection to condenser water per kW of cooling (Heat Dissipation Ratio)	2.5	1.8	1.8	<1.3
Condenser water duty relative to vapour compression	>1.9	>1.4	>1.4	1

Table 2 : Heat Rejection per kW of Chiller Output (Page 9, ETSU and ENVIROS, 2001)

Absorption chillers take on average 15 minutes to start and stop, compared with around 3 minutes for conventional chillers and they respond much slower to changes in load and hence are more suited to applications where load remains fairly stable. They are also larger; a 1.3 MW Carrier single effect hot water fired absorption chiller has an $8m^2$ foot print and is 2.9m high. An equivalent mechanical vapour compression water cooled chiller has a $4.5m^2$ footprint and is 2.1m high (Carrier, 2008), 2.5 times smaller in volume.

Coefficient of performance (COP), which is defined as the useful cooling output divided by the energy input for the whole cooling plant, is in the order of 0.68 for single effect absorption chillers, compared with a COP of at least 4 for conventional chillers. Absorption chillers are typical only sized to meet the base load and conventional chillers are usually provided to meet peak loads.

Although absorption chillers have fewer moving parts and hence should require less maintenance than conventional chillers, it is indicated in Good Practice Guide 256 that maintenance costs should be similar for both chiller types. This is because absorption chillers are not widespread in the UK, and hence availability of spare parts and trained maintenance specialists is limited.

In 2006, Keith Taylor from Trane, who manufacture absorption chillers, listed the following as the most common complaints about absorption chillers: crystallisation, slow response time, difficulties in operation and maintenance, large size and expense.

Glen Irwin a sustainability director from Foreman Roberts, an engineering consultancy, has undertaken absorption chiller feasibility studies for various projects and found that above 1MW of cooling, they emit less carbon dioxide than conventional chillers. But due to the initial cost, lack of maintenance engineers, bigger spatial requirements for heat rejection, the toxicity of the LiBr and running costs, has instead always installed more conventional chillers. He is more interested in adsorption chillers which he stated are much more reliable than absorption chillers and require only normal heat rejection rates.

2.5 Combined Cooling, Heating and Power

For decentralised electrical generation to offer environmental benefits over centralised generation, a significant proportion of the site's load must be supplied by CHP and all the waste heat produced must be consumed. Typically CHP plants are sized to meet the "base heating load", which is the heating demand of the site, which for the majority of the year is exceeded, i.e. the summertime heating load.

This load is typically several orders of magnitude less than the peak heating demand and the corresponding electricity produced generating this heat using CHP, is usually much lower than a site's total electrical demand. Therefore, the fraction of a site's energy from the CHP plant is often relatively small.

The addition of an absorption chiller does however increase the base heating load and hence possible size of the CHP plant, through introducing further heat demand in mid-season and summer. It may also reduce electrical demand, if the absorption chillers are displacing conventional chillers and hence the overall percentage of the site's energy from the CHP plant rises, which should lower carbon emissions. This is discussed further in Chapter 5.

2.6 Chapter Summary

Trigeneration is the decentralised generation of electricity using a combined heat and power engine. The waste heat from this process is then used for either space and domestic hot water heating purposes or to generate cooling in an absorption chiller.

In 2006, electrical generation from the 1,500 plus CHP plants in the UK was at an average efficiency of 67.7%, approximately 30% greater than the average efficiency of grid supplied electricity. To be cost effective, as a general rule of thumb, it is believed the units need to run for an average 14 to 16 hours a day, across the whole year. These loads are generally only seen in residential, university, hotel, leisure, museum and mixed use sites. Installation and maintenance costs are much greater than for conventional boiler plant but it is believed payback periods of within 5 years are possible if the scheme is sized correctly and there is a sufficiently high base heating load.

The most common type of absorption chillers are hot water fired, single effect units which are more than 6 times less efficient than mechanical vapour compression chillers and require nearly twice the heat rejection plant for equivalent cooling output. Absorption chillers are larger and more expensive but have less moving parts and so are usually more reliable.

Combined cooling, heating and power (CCHP) or Trigeneration, increases the base load requirement and hence running time of a CHP plant, it is believed this would normally result in lower emissions than conventional boiler and chiller plant.

The following chapter outlines the methodology as to how the feasibility of Trigeneration in the UK has been assessed.

3 Methodology

In order to assess the feasibility and likely success of mass implementation of Trigeneration across the UK, the following has been examined and is discussed in the proceeding chapters:

1) The performance of existing installations was investigated through the generation and issue of questionnaires to all known major Trigeneration suppliers and to multiple consultants, facilities managers and clients within the UK, with known experience with Trigeneration. The questionnaire was intended to obtain quantitative and qualitative feedback on existing installations and so enable the success of each to be evaluated.

   The questionnaire queried the following areas, which were deemed essential items in evaluating the success of a Trigeneration installation:

   - Delivered energy efficiency;
   - Proportion of total site load met;
   - Installation, operation and maintenance costs;
   - Reliability;
   - General opinion of the facility.

   From the twenty-seven questionnaires issued, completed questionnaires for 6 existing installations have been received and are reviewed in Chapter 4.

2) The Trigeneration facility at the Natural History Museum was visited in July 2008, to enable the evaluation of a facility in operation and to interview the former resident engineer to obtain feedback on performance. An assessment of the installation and a summary of the former resident engineers opinion is discussed in Chapter 4

3) A study examining the theoretical global warming impact of Trigeneration compared with modern conventional plant, in various scenarios, was undertaken. This examines the greenhouse gas emissions, specifically carbon dioxide and refrigerant emissions which contribute to global warming.

   The analysis looks at the predicted carbon emissions of:

   - A typical conventional grid electrical supply, boiler and chiller plant installation;

- A highly efficient conventional grid electrical supply, boiler and chiller plant installation;
- A typical Trigeneration facility;
- A highly efficient Trigeneration facility.

These four setups were selected as they were deemed to represent the likely average and best performance of Trigeneration and conventional plant installations and hence act as a basis for determining realistic and potential carbon emissions savings. For these four setups, the carbon emitted in producing the same electrical, cooling and heating energy output was calculated.

The proportion of the electrical, heating and cooling output from the facilities was then varied under ten different load scenarios, in order to determine the optimal performance range of each installation.

To reduce reliance on assumptions and increase the accuracy of the calculations, the plant efficiency data used for each installation was based on either: published information, for example BERR published CHP and power station efficiencies or performance data obtained from the six reviewed Trigeneration installations. Both the Building Regulation stipulated carbon emissions factors for Approved Document L compliance and the BERR published actual carbon emission factors for energy generation in 2006, were analysed to determine the effect these differing values have on the predicted carbon emissions. The calculation, results and assumptions are included in Chapter 5.

The global warming impact of refrigerants is a combination of that directly emitted as a green house gas in construction, operation and retirement of the refrigerant, plus the carbon dioxide which is indirectly emitted in the production of cooling energy at the chiller. The global warming impact of refrigerants is also discussed in this chapter by examining the global warming potential (GWP), as defined within the IPCC Second Assessment Report (1995). Unlike conventional mechanical vapour compression chillers, absorption chillers have refrigerants with a GWP of 0 and so the effect of this on total global warming impact is discussed.

The difference in water consumption for heat rejection in cooling towers at centralised power stations and that lost in evaporation in the cooling towers of decentralised Trigeneration plants, is examined based on published data for each. The impact of this water consumption is discussed.

Published data for sound pressure levels of conventional and Trigeneration facilities is also analysed, in relation to the permitted Noise Exposure Action Values of the Control of Noise at Work Regulations 2005.

4) The potential cost effectiveness of Trigeneration is evaluated, by comparing installation, operation and maintenance costs of a highly efficient 1 MW CHP engine and 700 kW absorption chiller, with a modern highly efficient conventional grid supply, boiler and chiller plant equivalent.

The analysis is based on published installation costs, gas and electrical energy unit rates and maintenance costs for the various plant items and the efficiency data derived in Chapter 5. Cost effectiveness is determined through analysis of the whole life cost, based on a 20 year plant life and payback period is also calculated. The assumptions and results of this analysis are discussed in Chapter 6.

5) The potential for wide spread usage of Trigeneration is discussed. This includes analysis of non-environmental and financial items obtained from the questionnaire results and literature review. The London decentralised energy target is for 50% of electrical energy to be generated locally by 2050. The carbon emissions reduction if 50% of delivered electrical energy in the UK could be generated in decentralised CCHP plants is calculated, based on the findings of Chapter 5. It is noted that further analysis would be needed to confirm the feasibility of this figure.

This is compared with published data for actual UK carbon emissions from delivered electricity and gas. Estimated emissions from wide spread installation of efficient CCGT power stations and highly efficient boilers and chillers is calculated based on the findings of Chapter 5. This is discussed in Chapter 7.

6) Low and zero carbon energy supply alternatives to Trigeneration, including biomass, ground source heat pumps, photovoltaics, solar thermal panels and wind turbines have been briefly discussed in Chapter 8. Some of the key advantages and disadvantages of each technology are highlighted based on published qualitative and quantitative data and consideration is given to whether any of these alternatives to Trigeneration, are likely to rival its environmental potential and cost effectiveness.

4 Existing Installations

Data for the following case studies is a summary of that obtained through questionnaire feedback, presentations and interviews with consultants, manufacturers and facility managers who have had experience with Trigeneration sites. Where available both qualitative and quantitative data has been examined to obtain an overall opinion of performance and success of each installation. A copy of the questionnaire and a summary of results for each case study, including sources, are included in Appendices A and B.

4.1 The Natural History Museum, London

Source: Questionnaire response, interview and presentation from Simon Tilleard, former resident engineer at the National History Museum. Simon now works as a Technology Manager for the London Climate Change Agency.

Rated Output:

1.82 MWe - electrical

1.9 MWth – heating

1.5 MWc – cooling

average every year?

Operational Efficiency: 82.7 %*

(*Excluding energy input for heat rejection).

Installation Cost: £3.7 million

Estimated Payback Period: 7.8 years

Simon Tilleard's Overview and Opinion of the Facility

The district heating plant at the Natural History Museum was originally installed in the 1950s and also served the Victoria and Albert Museum, Imperial College and Science Museum. When the Imperial College and Science Museum withdrew from the scheme in 2000, the subsequent rise in fixed and variable costs increased unit rate from 1.8p/kWh to 2.7p/kWh thermal output. The Museum decided to refurbish the aging plant, aiming to reduce the unit cost back to 1.8p/kWh thermal output. A life cycle cost analysis was undertaken and it was found that with the £3 million budget available, a conventional refurbishment would only reduce unit costs to between 2.2 and 2.5p/kWh thermal. However, after a detailed feasibility study, it was estimated that a 1.9 MW thermal CHP scheme could provide heat at a unit rate of 1.8p/kWh, within the budget available.

A Public Private Partnership ("PPP") was setup between Vital Energi and the Museum, in which Vital Energi would lease the main boiler plantroom from the museum, to install, operate and maintain a Trigeneration Facility. Two of the existing 12 MW boilers were refurbished and the remaining two removed and replaced with a CHP engine and two absorption chillers.

As part of the refurbishment, many of the distributed electrical chillers were replaced with a chilled water network linking 6 buildings to the centralised absorption chillers. It was not possible to remove all conventional chillers, as many spaces required chilled water flow temperatures below the 5°C capability of the installed lithium bromide absorption chillers. The facility became operational in late 2006, with the absorption chillers fully operational from July 2007. The Museum pays for the gas consumption and a unit price per kWh of electricity generated by the CHP plant.

The average unit rate for 2007 was equal to the 1.8p/kWh thermal output target and annual financial savings of £750,000 were achieved, compared with the existing installation. The quoted carbon reduction was 2.84 tonnes for 2007 and the scheme has helped attract a £3 million grant from the Treasury.

4.1.1 Comments from Site Visit

A site visit to the Trigeneration facility within the Natural History Museum was organised in July 2008, approximately 18 months after it became operational. The plant was in operation during the visit, with the CHP engine operating at maximum output to provide decentralised electrical supply and heating hot water to fuel the two absorption chillers.

The CHP engine is housed in an attenuated enclosure and ear protection is required within. Almost 90% of the heat generated by the engine is recovered from the flue and generator cooling system, the remainder is low grade heat which cannot be used to produce hot water. Noise from the absorption chillers was only audible within a few meters of the units and was negligible in comparison with the other plant operating within the facility. The CHP enclosure and absorption chillers, which provide up to 1.9 MW heating or 1.5 MW cooling, require approximately the same floor area as the two 12.5 MW boilers housed in the same plantroom.

In discussion with Simon Tilleard, the former resident engineer who was responsible for the installation, he attributed the success of the facility to the appointment of an experienced Danish contractor, who installed, operates and maintains the entire facility. He reported no major reliability issues and that both Vital Energi and the Museum were very happy with the installation. He indicated the museum is currently considering enlarging the facility to meet a higher proportion of the site's energy loads.

4.1.2 Case Study Conclusions

The scheme can be considered both a financial and environmental success for the museum, as the unit energy price has reduced by 33%, the scheme has a payback period of within 8 years and carbon emissions have decreased. The success appears to be at least in part due to an experienced contractor who designed, installed and operates the facility. The new CHP engine and absorption chillers do however replace aging existing plant, some of which is 50 years old and so it is of no surprise the new equipment outperforms it. It is noted that the maximum output of the CHP engine is several orders of magnitude lower than the peak boiler load, suggesting the scheme is undersized and hence is always operating at close to maximum output, with minimal dumping of waste heat. If the scheme were to be upgraded, such as to provide a greater proportion of the site's heating load and to reduce reliance on conventional chiller usage, it is questionable whether the environmental performance would be as great.

Figure 11: Thermax Absorption Chiller and GE Jenbacher Reciprocating CHP Plant (Installed as part of the Natural History Museum's Trigeneration Facility)

4.2 Citigen Ltd, London

Source: Questionnaire response from John Bradshaw, Production Coordinator, working at Citigen Ltd.

Rated Output:

31.6 MWe - electrical

25 MWth - heating

11.2 (Absorption) + 4.2 (Electric) MWc - cooling

Operational Efficiency: 70.2% (2007)*

(*Facility has generally been operating at between 50 and 70% efficiency up until 2007)

Installation Cost: £80 million

Estimated Payback Period: the facility to date has operated at a loss.

John Bradshaw's Overview and Opinion of the Facility

Citigen is a large scale Trigeneration facility in north London, which became operational in 1995, originally intended to be a flagship scheme for replication elsewhere in the country. All electricity generated is exported to a local distribution network and all heating and cooling energy distributed through a network to a number of City of London and private customers, including; the Museum of London and the Barbican centre. Citigen, originally a partnership between British Gas and Utilicom, undertook the design, which was sized to meet load profiles of 13 consumers. A 3.6 km long variable volume heating hot water network, serves all 13 customers and a 2.4 km long variable volume chilled water network, serves 6 customers.

Generally each consumer has a plate exchanger linked to the networks, enabling desired secondary flow temperatures (usually 82°C heating/6°C cooling), with a 100% turndown ratio, so that demand and supply can match. Billing is determined via an energy meter across the flow and return connections to each plate exchanger, which measures flow rate and change in temperature and hence consumed heating or cooling energy.

Customers benefit from reduced local emissions, plus most no longer require refrigerants or fuel supply for heating appliances on site. Cooling towers or other heat rejection plant is generally no longer needed and plant noise has been reduced. Also tariffs are reported to be less; there is reduced plant spatial requirements and lower capital and maintenance costs.

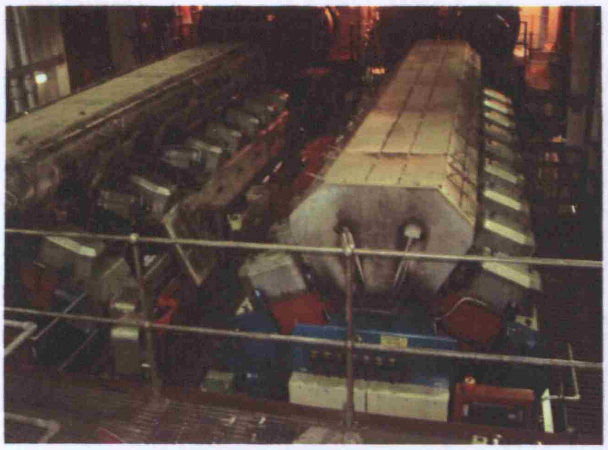



Figure 12: ENER.G CHP Engines and Trane Absorption Chiller at Citigen

4.2.1 Case Study Conclusions

This facility has been an economic success for end consumers but from the operator's perspective the scheme itself cannot be considered successful, as it has suffered from major reliability problems and has operated at a loss for each of its thirteen years of operation. Multiple changes in ownership and rising gas prices have been major factors in this but ultimately unless operating efficiency can be kept above 70%, rather than fluctuating between 50 and 70% as it has, it is likely to continue to operate at a loss.

4.3 West Quay, Southampton

Source: Questionnaire response from Craig Grobety, Energy Technician at Utilicom, designers, installers and operators of the CCHP facility.

Rated Output:

6.4 MWe – electrical

31.1 MWth – heating

9.3 MWc – cooling

Operational Efficiency: 73.7 %

Installation Cost: £4 million

Estimated Payback Period: 8 years

Craig Grobety's Overview and Opinion of the Facility

In the centre of Southampton there is a large district heating and cooling network serving many of the city's large buildings; including the Acre West Quay Shopping Centre, De Vere Grand Harbour Hotel, BBC TV Studios and a swimming and diving complex. This system is primarily a CCHP scheme but incorporates some geothermal and conventional boiler heat input in peak periods. All electricity generated is exported to a local distribution network.

The CCHP plant has operated at an average efficiency of 73.7% between 2005 and 2007, generates a profit and has an estimated payback period of 8 years. Despite the success of the scheme, it has struggled to attract additional big consumers, which would make the scheme even more cost effective.

Utilicom, who developed, installed and operate the plant, have estimated that district cooling is 50-100% more expensive to install and operate than a district heating scheme of the same capacity. This is due to the larger pipes and additional required pumping energy, a result of the smaller flow and return temperature difference of chilled water, at 8°C compared with 30 °C difference for heating water. It is therefore only considered cost effective for core buildings near the facility to be connected to the district cooling main.

4.3.1 Case Study Conclusions

The scheme can be considered a financial success as it has a payback period of within 8 years but it is unknown whether it offers environmental benefits over decentralised boiler and chiller plant and grid supply electricity. It is unclear why there have been difficulties in attracting further customers to join the scheme and whether there would be similar problems for similar schemes in the future. The implication that for district cooling to be cost effective, end users must be close to the facility, is crucial, as it puts a limit on the geographical size at which a scheme can operate at a profit.

Figure 13: Southampton District Heating and Cooling Network

4.4 The Met Office, Exeter

Source: Presentation from Julian Packer, Director at Cogenco, who installed and operated the facility.

Rated Output:

1.5 MWe – electrical

1.69 MWth – heating

1.0 MWc – cooling

Operational Efficiency: Unknown

Installation Cost: Unknown

Estimated Payback Period: Unknown

Julian Packer's Overview and Opinion of the Facility

As of May 2006, Cogenco had 531 CHP units in operation, providing 186 MW of electrical output, the Met Office is one of the few of these which is a CCHP installation. Cogenco designed, operate and maintain the facility, which primarily uses the waste heat from the CHP engine to drive absorption chillers, for cooling of IT equipment and for comfort cooling of offices. The facility also provides some heating energy for space heating and to generate domestic hot water.

The facility operated between January 2004 and late 2005, reducing consumed energy and carbon emissions by 21%, before operation was suspended due to "adverse spark spread". This means the difference in price of purchasing grid supplied electricity and the cost of generating it on site, was not sufficient for the scheme to be cost effective, due to the high cost of gas.

4.4.1 Case Study Conclusions

This scheme is clearly a failure, in that it is so expensive to operate in comparison with conventional plant, that it has been decommissioned. Claims of a 21% reduction in carbon emissions over the existing plant were, however, promising but clearly this is less crucial to the client than cost. This scheme is cooling lead rather than heating lead which is likely to be a key reason for poor financial performance. The COP of a single effect absorption chiller is on average six times less than a standard mechanical vapour compression chiller and hence requires six times the energy input to achieve the same output. It would perhaps have been better had the waste heat from the CHP engine been used for space and domestic water heating purposes and the generated electricity used to fuel an efficient conventional chiller.

Figure 14: Met Office Cummins QSV91 CHP Engine

4.5 George Square, University of Edinburgh

Source: Presentation from and correspondence with David Barratt, Engineering Operations Manager at the University of Edinburgh.

Rated Output:

1.6 MWe – electrical

1.7 MWth – heating

0.6 MWc – cooling

Operational Efficiency: 69.2%*

*Ignores electrical input associated with heat rejection from chillers.

Installation Cost: £1.6 million

Estimated Payback Period: 7 years

David Barratt's Overview and Opinion of the Facility

The University of Edinburgh has so far invested £12 million in three CHP networks, the George Square network is the first to utilise absorption cooling. The installation incorporates 75m^3 of thermal storage to assist with load levelling, thus maximising CHP output and minimising dumping of heating energy. A new LTHW network was installed to replace the inefficient 1950s steam heating network and a comprehensive controls system provided to automate operation efficiently, see Figure 15.

Figure 15: George Square, Trigeneration Schematic (Courtesy of University of Edinburgh)

The scheme is on average 69.2% efficient, see Figure 16, and achieves carbon savings of 1,254 tonnes per year. There is in place an operation and a maintenance contract with the supplier, which guarantees availability and has so far ensured good reliability. Although maintenance costs have increased, from that of the original steam heating system and conventional chiller installation, the facility has an estimated payback period of less than 7 years.

4.5.1 Case Study Conclusions

The scheme can be considered both a financial and environmental success for the university, as it has a payback period of only 7 years and carbon emissions have decreased. The new CHP engine and absorption chillers do, however, replace aging existing plant, some of which is 50 years old and so it is of no surprise the new equipment outperforms it. It is noted that despite the short payback period and the fact that the scheme incorporates thermal storage, it is surprisingly the least efficient of all the case studies reviewed. It is not clear the reason for this but it does suggest the scheme is underperforming.

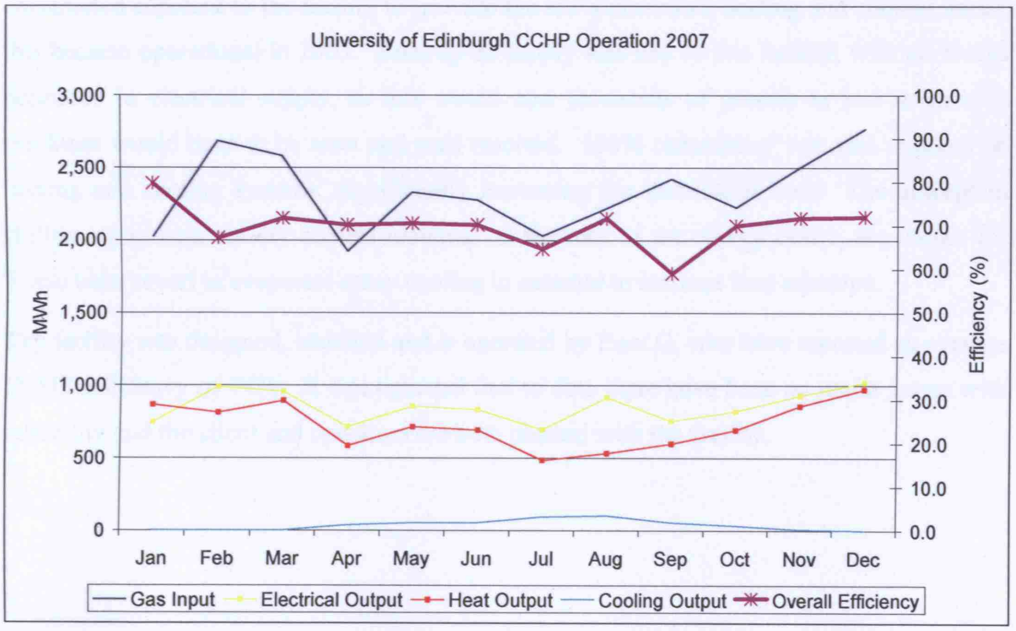


Figure 16: University of Edinburgh CCHP Input, Outputs and Efficiency 2007

4.6 Royal Mail, Slough

Source: Presentation from Alan Barlow, Managing Director of Ener.G, who installed and operates the facility.

Rated Output:

3.0 MWe – electrical

3.5 MWth – heating

1.4 MWc – cooling (plus 3.6 MW from Mechanical Vapour Compression chillers)

Operational Efficiency: 74%

Installation Cost: £6 million

Estimated Payback Period: Unknown

Alan Barlow's Overview and Opinion of the Facility

The Royal Mail Group Facility, in Slough, encompasses an automated mail sorting centre and associated offices, totalling 50,000m^2. A dedicated Trigeneration Energy Centre was constructed adjacent to the facility to provide the site's electrical, heating and cooling needs, this became operational in 2003. Security of supply was key to this facility, with no breaks permitted in electrical supply, as this would cost thousands of pounds in lost revenue as machines would have to be reset and mail resorted. 100% redundancy was also required on heating and cooling systems, significantly increasing the installation cost. The absorption chillers reject heat via dry coolers mounted on the roof of the energy centre, see Figure 17. These units revert to evaporate spray cooling in summer to increase heat rejection.

The facility was designed, installed and is operated by Ener.G, who have reported an average CCHP efficiency of 74%. It was reported that to date there have been no major issues with reliability and the client and operators are both pleased with the facility.

Figure 17: Dry Coolers for Heat Rejection from the Absorption Chillers, incorporate Evaporate Spray Cooling in summer

4.6.1 Case Study Conclusions

The efficiency and carbon performance of this facility is relatively high and so it can be considered an environmental success. It is noted that unlike the Met Office facility, the majority of cooling output is from conventional chillers, rather than absorption chillers. The financial success of this installation is unknown but because 100% redundancy was required on all plant items, greatly increasing the installation cost, it is envisaged that it will have a long payback period.

4.7 Chapter Summary

Facility	Installation Cost (£millions)	Efficiency (%)	Positives	Negatives
Natural History Museum	£3.7 (7.8 year payback period)	82.7*	High efficiency, short payback period, attracted funding and inspired future schemes.	Only delivers a relatively small proportion of the total site's load and so carbon emissions savings are limited.
Citigen Ltd	£80.0 (payback period unknown)	70.2	Offers customers financial savings and reduces requirement for on-site plant.	Generally poor efficiency to date and operates at a loss.
West Quay	£4.0 (8 year payback period)	73.7	Relatively high efficiency, short payback period.	Struggled to attract additional customers.
Met Office	Unknown	Unknown	Offered carbon emission savings over previous installation	Not cost effective and so operation was suspended within two years.
University of Edinburgh	£1.6 (7 year payback period)	69.2*	Short payback period and offers carbon emission savings over previous installation.	Relatively poor efficiency.
Royal Mail	£6.0 (payback period unknown)	74.0	Relatively high efficiency. Excellent reliability.	Expensive, due to 100% redundancy requirements.

Notes:

*Ignores electrical input associated with heat rejection from chillers

Table 3 : Summary of Case Studies of Existing Trigeneration Facilities

Due to the limited number of existing CCHP plants and the reluctance of clients, suppliers and consultants to share financial, energy and carbon performance data, the study of Trigeneration facilities was limited to six installations. This relatively small pool of data makes it difficult to make accurate statistical conclusions; however, the results do show several clear trends.

It is important to note that half of the questionnaires were completed by representatives of the companies who designed, supplied and operate the trigeneration equipment and that it is in their interest that the facilities are seen to be efficient and cost effective. Despite this, the responses from these representatives do not appear to exaggerate the success of their respective schemes and are generally considered a relatively unbiased evaluation.

Four of the six installations examined can be considered a success in terms of reliability, financial and environmental benefits. Of the remaining two, the Citigen installation is the oldest project and a pilot scheme and many lessons have likely been learnt from it. It also suffered from multiple changes of ownership. Improvements have been reported since the current owners E-On took charge and the efficiency did increase to more than 70% in 2007. The Met Office installation, despite being 74% efficient has struggled to break even, due to reported 'adverse spark spread'. This is the only scheme which is cooling led, as opposed to heating led, and this could be a key factor in its failure to be cost effective. This is discussed further in the following chapter.

Three of the six installations estimate payback periods of within 8 years and so could prove more cost effective than modern conventional plant. Payback periods are discussed further in Chapter 6.

Of the six case studies examined, all those serving existing buildings claim carbon savings over the previous electrical grid supply system, boiler and chiller plant installations. This is, however, no surprise, as the installations were typically replacing 50 year old boiler and aging chiller plant, with modern units. The important question is whether the carbon savings are greater than if modern high efficient condensing boilers and mechanical vapour compression chillers were installed, at considerably less, this is examined in the next chapter.

5 Potential Environmental Benefits of Trigeneration

This Chapter evaluates the potential environmental benefits of Trigeneration compared with conventional plant, through consideration of the following;

- Carbon emissions.
- Global warming impact of refrigerants.
- Water consumption.
- Noise emissions.

5.1 Energy Efficiency and Carbon Emissions

In 2006, the average efficiency of delivered electricity in the UK was 38%. Despite coal power stations being the most carbon intensive and on average only 36% efficient, these produced more electricity than any other power station type, see Table 4. The most efficient fossil-fuelled power stations are combined cycle gas turbines (CCGT), which are on average 49% efficient, with the newest stations such as a Coolkeeragh in Northern Ireland, as high as 55% efficient. The quoted carbon emissions values in the table do not include the 7.5% distribution losses between the power station and end user.

Power Station Type	Fuel Input in Million Tonnes of Oil Equivalent	Fuel Input in GWh (1 tones oil = 11,630 GWh)	Electrical Output GWH	Average Efficiency %	Tonnes CO_2 /GWh (inc distribution losses)	Total CO_2 (Tonnes) (inc distribution losses)
Coal	35.871	417,180	150,283	36	876	131,698,002
Gas	26.636	309,777	141,342	46	370	52,343,654
Nuclear	17.131	199,234	75,451	38	-	
Other renewables	-	-	9,947	-	-	-
Oil	1.433	16,666	4,999	30	590	2,951,076
Hydro	-	-	4,605	-	-	-
Wind	-	-	4,232	-	-	-
Other	1.529	17,782	3,615	20	-	-
Total production	**82.6**	**960,638**	**394,474**	**41**	**480**	**189,479,011**

Notes:
*Note the efficiency figure quoted for gas power stations includes both CCGT and the older less efficiency steam turbine power stations.

Table 4 : UK Delivered Electricity 2006 and Power Station Efficiency (BERR, 2007)

CCHP reduces the grid electricity requirements of a site and increases the gas consumption, as electricity is generated locally by a gas fired CHP engine. The electrical consumption is further reduced as absorption chiller plant requires less electricity than conventional mechanical vapour compression chiller plant. In 2006, the carbon emissions factor for gas was 0.206 kg CO_2/kWh and the factor for delivered electricity more than 2.5 times greater at 0.519 kg CO_2/kWh (BERR 2007). For these reasons Trigeneration is seen as a low carbon alternative to a grid electrical supply and conventional boiler and chiller installations.

where is it?

5.2 Building Regulations Approved Document L

Fuel	Carbon emissions Factor (kg CO_2 / kWh)	
	Approved Document L (2006)	UK 2007 data published by BERR (2007)
Natural Gas	0.194	0.206
Oil	0.265	0.258
Coal	0.291	0.346
Electricity Generated from CHP	-	0.295
Grid Supplied Electricity	0.422	0.48
Electrical Generation from Fossil Fuel Power Stations	-	0.631
Electrical Generation from Coal Power Stations	-	0.876
Electrical Generation from Gas Power Stations	-	0.370
Grid Displaced Electricity	0.568	0.43[1]

Notes:
[1] - This factor is quoted as applicable for calculated carbon savings for long term analysis.
All values exclude the BERR quoted grid electrical distribution losses of 7.5%

Table 5 : Carbon emissions Factors

Approved Document L of the Building Regulations 2006, is the tool by which designers must evaluate a new or refurbished building's predicted carbon emissions and meet reduction target values. The reduction target is based on a notional building of the same geometry as the actual building but with the worst case permitted building constructions heat loss and plant efficiency values and a defined percentage of glazing. The actual building must have a carbon emissions rate of approximately 28% less than the notional building, to comply with the UK Building Regulations.

There is much debate over which carbon emissions factor should be taken for grid electricity and grid displaced electricity, which is the emissions rate deducted in the above calculation, where CHP is used in place of grid supply electricity, see Table 5. The regulation defines carbon emissions values for this calculation, with grid electricity taken as 0.422 kg CO_2/kWh and grid displaced electricity taken as the higher value of 0.568 kg CO_2/kWh.

Although not released until 2006, these values are based on studies by the Building Research Establishment (Pout, 2002) and the Department for Trade and Industry (2000), which come from actual emissions data for 1998/1999. The carbon emissions factor for grid electricity at this time was 0.568 kg CO_2/kWh and hence is used as the value for deducting from the actual building, where grid electricity is displaced. The value used for carbon emissions for grid electricity, is taken from the DTI report of 2000, which predicted the mix of power station types from 2005-2010 would produce an average carbon emissions rate of 0.422. This is in fact 19% less than the average emissions rate in 2005 and 2006, allowing for distribution losses.

In relation to this there are two irregularities with the Building Regulations calculation; firstly why use a higher factor for grid displaced electricity than grid supplied, and secondly why is a grid displaced value required at all, if the building is compared with a notional building with grid supply electricity. Both these items favour CHP and perhaps over-estimate its true benefit in reducing carbon emissions from buildings. In discussion with Phil Jones, the head of the CIBSE CHP group and organiser of two full day Trigeneration seminars, he highlighted the disagreement across industry as to what the appropriate carbon factors for analysis of environmental performance should be.

5.3 Carbon Emissions Calculations

The following calculations examine the energy input and carbon emissions of conventional and Trigeneration installations, in various scenarios, to achieve the same output. To determine this, several assumptions have been made and are listed in Appendix C1.

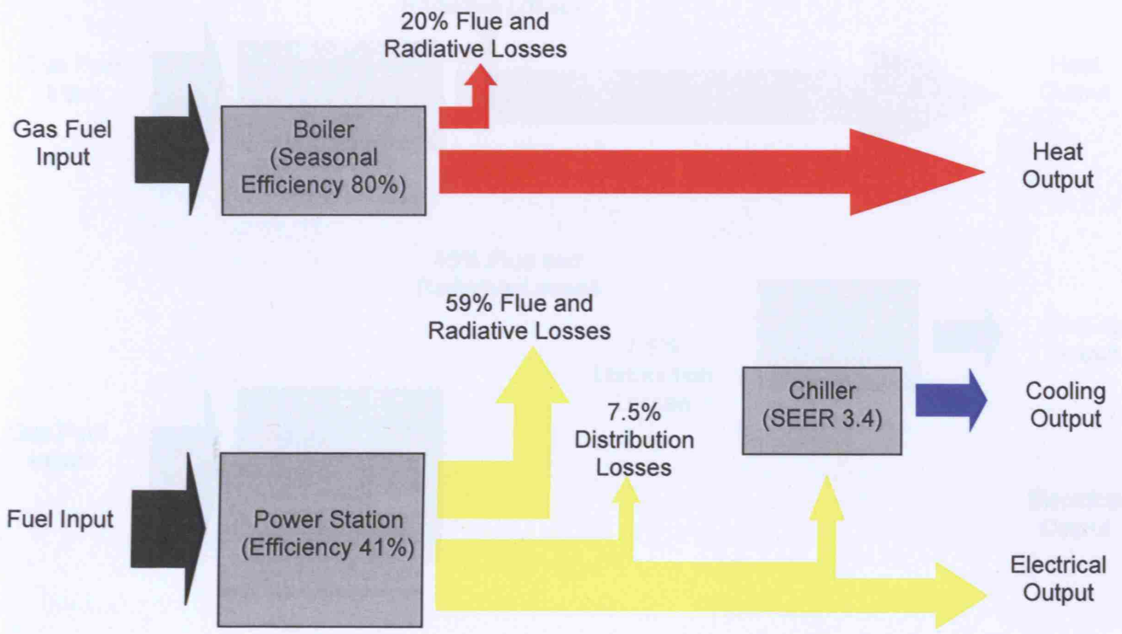
5.3.1 Scenarios Used for Analysis

In order to analyse carbon performance of conventional and Trigeneration installations, the following scenarios have been derived:

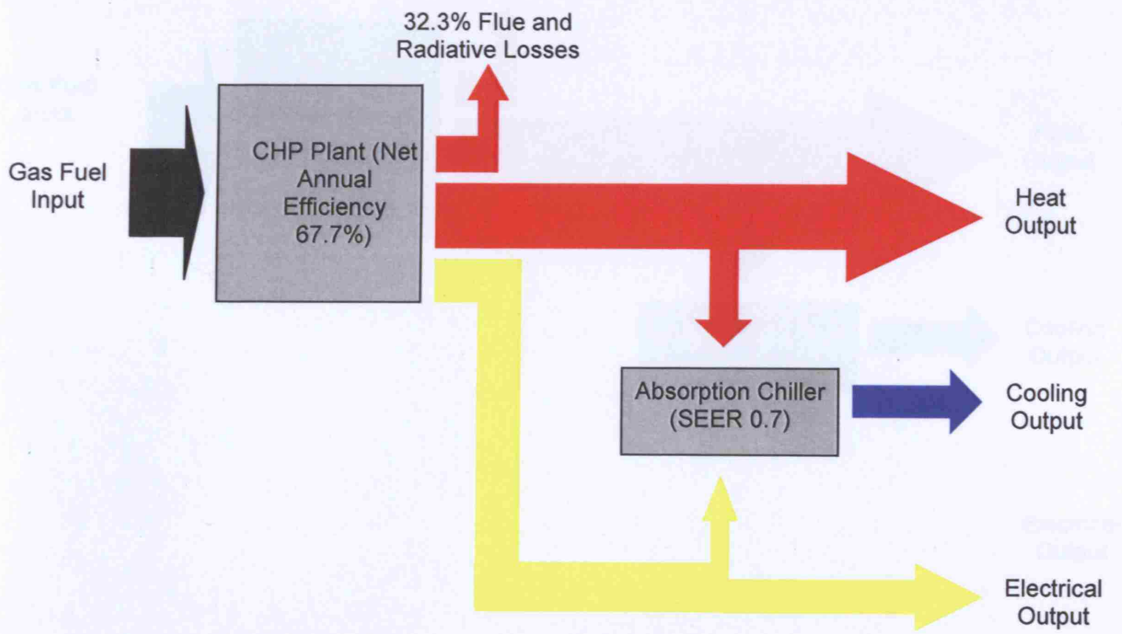
- Scenario 1 is intended to represent typical installed conventional boiler and chiller plant, with grid electricity connection and is so the benchmark for comparison. This is the scenario under which Trigeneration must have lower carbon emissions than, if it is to be considered a low carbon alternative to conventional plant.
- Scenario 2 represents what would be the normal output of a Trigeneration facility based on published performance of over 1,500 installed CHP engines in the UK and the normal single effect absorption chiller efficiency.
- Scenario 3 represents modern highly efficient boiler and chiller plant, with grid electrical connection from the most efficient combined cycle gas turbine power station. This is the scenario which represents the most efficient plant currently in use and perhaps the likely typical carbon performance of UK conventional electrical, heating and cooling generation in ten years time.
- Scenario 4 represents the likely maximum performance of a Trigeneration facility based on the delivered energy from the Natural History Museum Facility, the most efficient installation reviewed.

These four scenarios are illustrated graphically on the following pages.

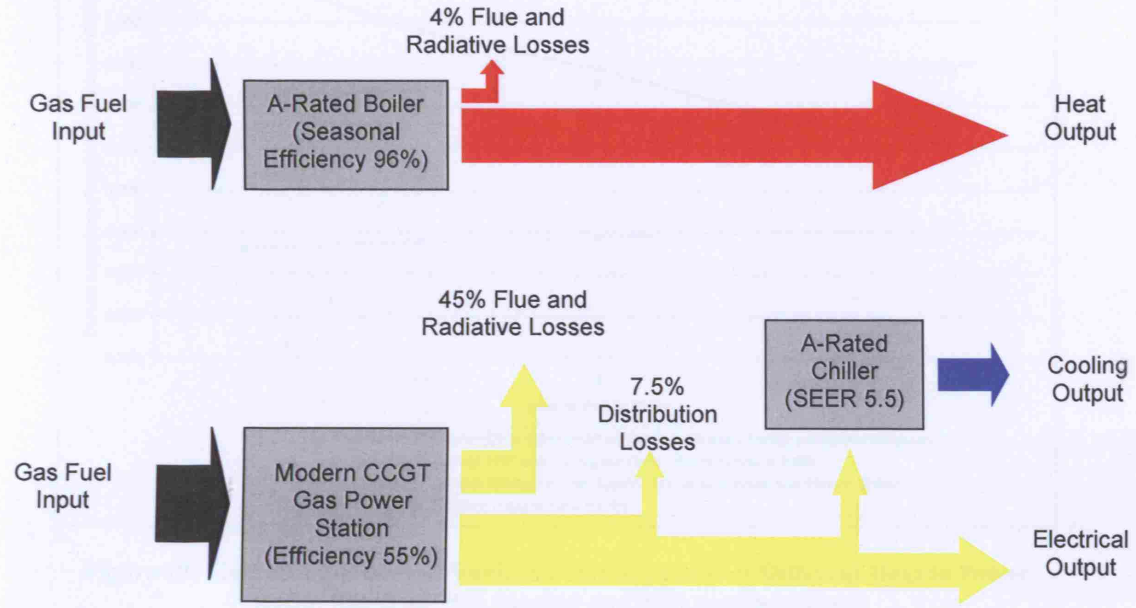
Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency



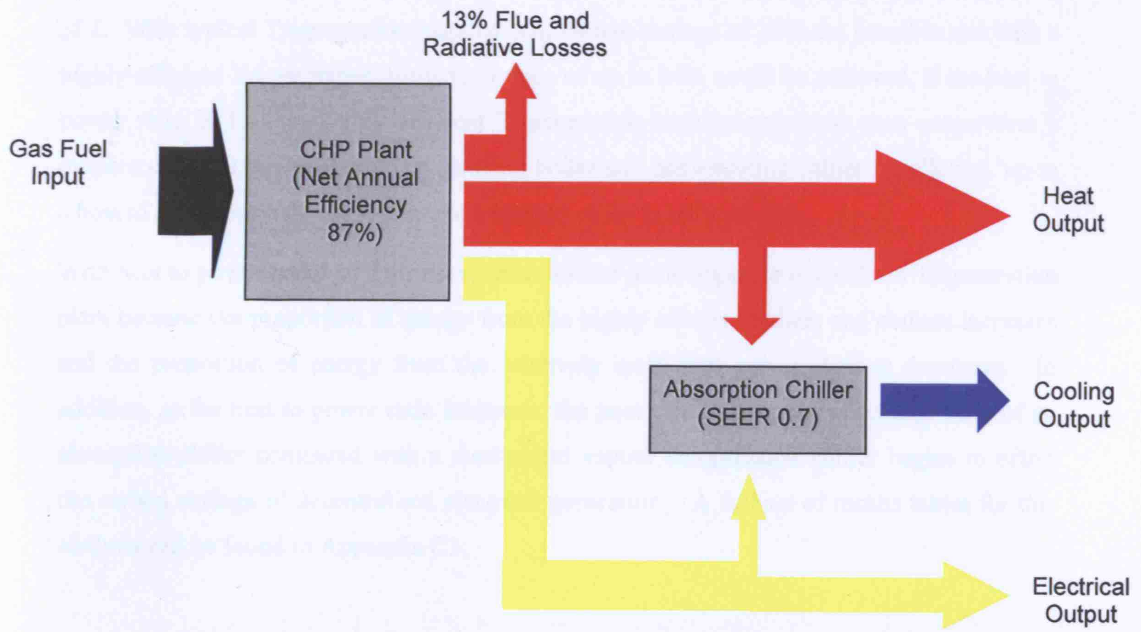
Scenario 2: Typical CHP and Absorption Chiller Performance in 2006



Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional chiller



Scenario 4: Efficient Trigeneration Facility



5.4 Results of Carbon Emissions Study

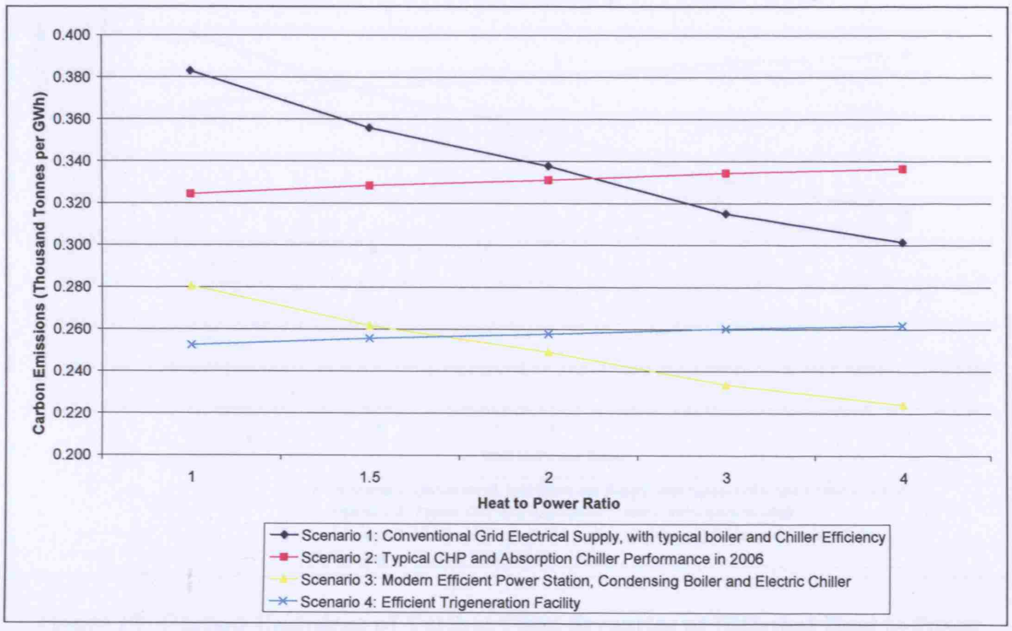


Figure 18: Carbon Emissions of Various Plant Scenarios at Different Heat to Power Ratios based on 75% heating and 25% cooling output

Figure 18 shows carbon emissions predictions for conventional and Trigeneration installations, for various heat to power ratios, where 75% of the annual heat output is used for heating and 25% for cooling purposes. Typical Trigeneration facilities in this instance have lower emissions, compared with typical conventional installations, up to a heat to power ratio of 2. With typical Trigeneration installations, carbon savings of 15% are possible and with a highly efficient Trigeneration facility, savings of up to 34% could be achieved, if the heat to power ratio is 1:1. A highly efficient Trigeneration installation would even outperform a modern efficient power station, condensing boiler and conventional chiller installation, up to a heat to power ratio of 1.5, with carbon savings of up to 10% possible.

With heat to power ratios of 2 or more, conventional plant begins to outperform Trigeneration plant because the proportion of energy from the highly efficient boilers and chillers increases and the proportion of energy from the relatively inefficient power stations decreases. In addition, as the heat to power ratio increases, the poor seasonal energy efficiency ratio of an absorption chiller compared with a mechanical vapour compression chiller begins to offset the carbon savings of decentralised electrical generation. A full set of results tables for this analysis can be found in Appendix C1.

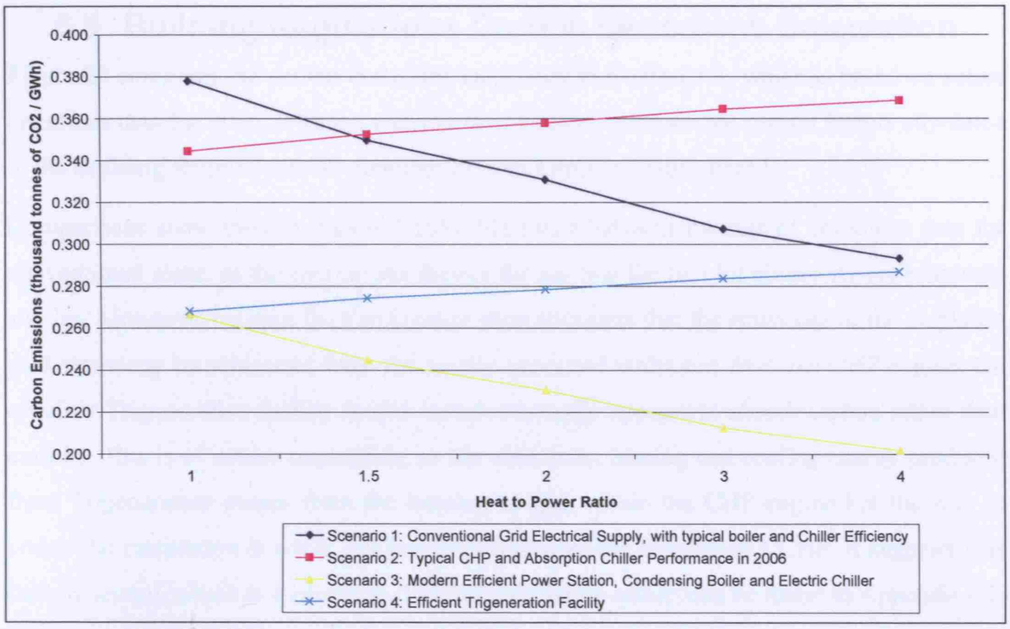


Figure 19: Carbon Emissions of Various Plant Scenarios at Different Heat to Power Ratios based on 50% heating and 50% cooling output

Figure 19 shows the same four scenarios as Figure 18 but instead represents 50% of the annual heat output used for heating and 50% for cooling, rather than 75/25. The results show a 9% carbon reduction can be met, at a heat to power ration of 1:1, when comparing typical installations. At higher heat to power ratios Trigeneration facilities will have greater carbon emissions than conventional facilities. The result also shows that modern CCGT power station and efficient conventional chiller and boiler will have better carbon performance at all heat to power ratios. A full set of results tables for this analysis can be found in Appendix C1.

Overall the two sets of results suggest Trigeneration can provide carbon savings over conventional plant but only if the heat to power ratio is less than 2:1 and if the hot water produced by CHP is primarily used for heating purposes rather than to generate cooling in an absorption chiller, as was the case for the Met Office installation examined in Chapter 4.

The above analysis assumes that 100% of the heat produced by the CHP plant is utilised for heating or cooling and hence none is "dumped". To maintain carbon efficiency it is crucial the majority of the heat produced by the CHP engine is consumed and so ideally facilities should be heat lead and not electrically lead, i.e. output is matched to the heating demand rather than the electrical demand of a site. The facility should also be configured to export any additional electricity to the grid.

The above analysis does not consider any possible losses associated with district heating and cooling or local electrical distribution, this is discussed in Chapter 7.

5.5 Building Regulations Carbon Emissions Calculation

Figure 20 compares the carbon emissions calculated in Section 5.4, which is based on actual emissions data for 2006, with the equivalent emissions based on the carbon factors stipulated in the Building Regulations, for compliance with Approved Document L.

Comparisons show there is only a 7-15% difference between the sets of emissions data for conventional plant, as the two carbon factors for gas and the two for electricity are relatively similar. However, because the Part L calculation stipulates that the emissions of the displaced grid electricity be subtracted from the locally generated emissions from the CHP engine, the efficient Trigeneration facility in this instance actually appears to absorb carbon rather than emit it. This is of course impossible, as the electricity, heating and cooling energy produced from Trigeneration comes from the burning of gas, within the CHP engine but the way in which the calculation is setup, not just over-estimates the benefits of CCHP, it suggests it is carbon neutral, which is misleading. The full calculation results can be found in Appendix C2.

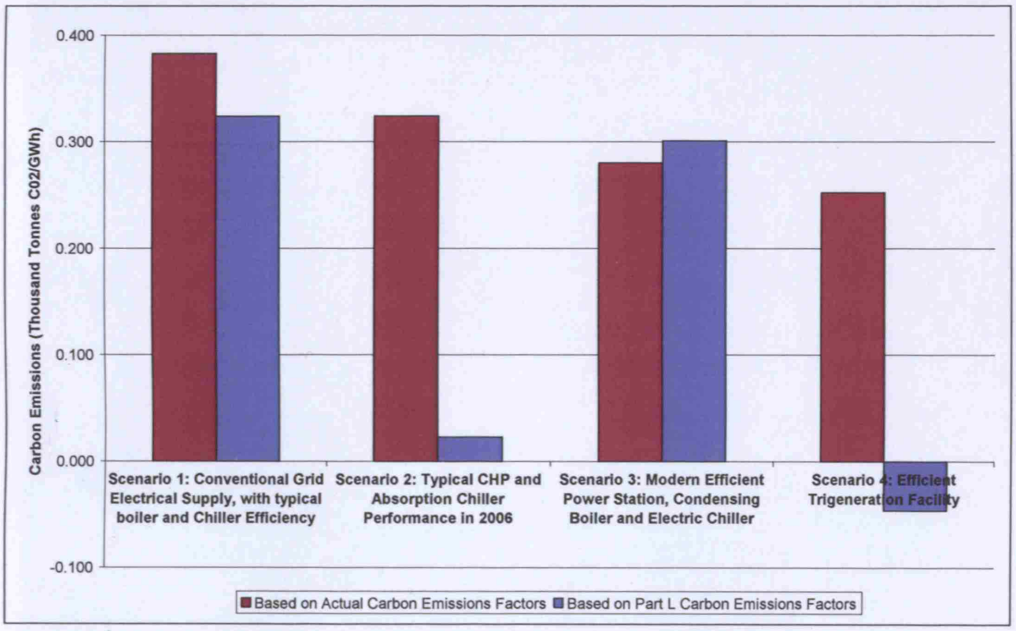


Figure 20: Difference between Carbon Emissions when using actual and Approved Document L carbon factors, with a heat to power ratio of 1 and heating to cooling ratio of 75/25

5.6 Environmental Impact of Refrigerant Usage

Most refrigerants in use in the UK today have zero ozone depletion potential and a global warming potential (GWP), as defined within the IPCC Second Assessment Report (1995), of between 1,300 and 2,000. This means that each kg released is potentially 2,000 times more harmful than carbon dioxide. The global warming impact of refrigerants is a combination of that directly emitted as a green house gas in construction, operation, leakage and retirement of the refrigerant; plus the carbon dioxide which is indirectly emitted by conventional and absorption chillers in the production of chilled water for cooling purposes. The refrigerants used in absorption chillers have zero ozone depletion and global warming potential.

In the 1970s, annual refrigerant volumetric loses of 30% through system leakage, were not untypical but now losses are usually less than 0.5% and hence the global warming impact is greatly reduced (Calm J., 2005). This is likely to reduce further with the recent introduction of the F-Gas Regulations, which require leakage inspection in 3-12 month intervals, depending upon the refrigerant volume. Refrigerant leak detection systems will also be required on all large systems by 2010.

The carbon dioxide emitted by electric and absorption chillers in chilled water production, therefore, normally contributes more than 99% of the refrigerants overall environmental impact (Calm J., 2005) and hence this greatly overshadows the hydro-fluoro-carbon emissions from refrigerants with a high GWP.

Therefore with respect to the global warming impacts from the generation of cooling energy, the refrigerant emissions of mechanical vapour compression chillers make a negligible difference to the global warming impact.

5.7 Plant Noise Levels

Absorption chillers have fewer moving parts than mechanical vapour compression chillers and as a result are quieter. Table 6 shows the sound power levels for a Carrier 1.3 MW absorption and a Carrier 1.3 MW water-cooled mechanical vapour compression chiller, overall the absorption chiller is 12 dB(A) quieter at 1m.

Unit	Sound Pressure Levels at 1m (dBA)							
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	O/All
Carrier 16LJ 1.3 MW Absorption Chiller	49	57.5	65.7	67.5	68	63	59	**73**
Carrier 30HXC375-PH3 1.3 MW Mechanical Vapour Compression Chiller	46.9	59	64	80	82	76	65	**85**

Table 6 : Chiller Acoustic Data (Carrier, 2008)

CHP engines, unlike boiler installations, normally require attenuated enclosures and careful positioning of the exhaust, to limit disturbance. This marginally increases the installation cost and spatial requirement in comparison with conventional plant.

An acoustic enclosure is provided for the Natural History Museum CHP engine and ear protectors are required under The Control of Noise at Work Regulations 2005 (Health and Safety, 2005) when maintaining the engine. The enclosure is, however, sufficient to reduce the noise of the CHP engine to 70 dBA, at 1m outside the enclosure walls (Vital Energi, 2007). This is below the defined lower noise exposure action value of the regulations and hence ear protectors are not required to be worn outside the enclosure.

5.8 Water Consumption

Nationally 50% of all water consumption is used for cooling of power stations, which equates to approximately 1,136 to 1817 litres/MWh, with water consumption in decentralised CHP plants negligible in comparison (Allan Jones, 2007). Water shortages are a potential problem in the south east of England, where dry summers can result in "droughts" and water consumption has to be restricted. Increasing decentralised energy generation could therefore reduce UK water consumption, treatment and pumping energy and the likelihood of restrictions on consumption.

Absorption chillers do, however, require twice the heat rejection plant capacity as mechanical vapour compression alternatives and so when coupled with cooling towers or spray coolers, twice the volume of water is lost to evaporation. Approximately 1,500 litres per MWh are lost in evaporation in cooling towers (ETSU and ENVIROS, 2001) and so hence twice this for absorption chiller installations.

Typically the cooling output of a CCHP installation is less than the electrical output and so overall there should still be a reduction in water consumption with CCHP.

5.9 Chapter Summary

Analysis has shown that carbon emissions per GWh output from a Trigeneration facility can be as much as 34% less than those emitted from typical conventional plant. In comparison with a modern conventional boiler and chiller plant installation, supplied with electricity from an efficient CCGT power station, Trigeneration carbon emissions are 10% less. In order to realise carbon savings, the majority of generated heat should be consumed and Trigeneration facilities should have a heat to power ratio of 2 or less. In addition to this, most of the heat energy generated by the CHP engine should be used for heating purposes, rather than to generate cooling in an absorption chiller. Trigeneration becomes more carbon intensive as the ratio of cooling to heating output increases and hence is best suited to sites with dominant heating loads.

When using the Building Regulations method for determining carbon emissions and the stated carbon factors for analysis, Trigeneration carbon emissions appear several magnitudes lower, than when analysed using current actual emissions data. Under certain circumstances Trigeneration can even appear to be carbon neutral, despite all electrical, heating and cooling energy being generated from burning natural gas on site. This greatly over-exaggerates the carbon savings possible with Trigeneration.

The global warming impact of fluorinated refrigerants was found to be negligible in comparison with the carbon emissions generated in the production of cooling energy. The seasonal energy efficiency rating of a chiller is therefore considerably more important than whether the refrigerant has a global warming potential of 0 as with absorption chillers or up to 2,000 with mechanical vapour compression chillers.

Plant noise is increased with Trigeneration installations, due to the added noise of the CHP engine; this is relatively easily mitigated if the plant is located in a noise sensitive area, through installing the CHP engine within an acoustic enclosure and with careful positioning of the flue. Water consumption is reduced with Trigeneration, providing the proportion of electrical output exceeds that of the cooling output.

In the next chapter the cost effectiveness of Trigeneration is examined.

6 Financial Benefits of Trigeneration

In order for Trigeneration to be considered financially viable it must be similarly or more cost effective than conventional plant. Financial analysis of CCHP must not only take into account installation costs but also operational and maintenance costs, so as to determine the whole life costing of the installation. This chapter examines the theoretical whole life cost of a 1 MW (electrical and thermal) CHP engine and 700 kW absorption chiller, with conventional plant of the same capacity.

6.1 Whole Life Cost Analysis

The following calculation estimates the installation and running costs of highly efficient conventional and Trigeneration installations, i.e. Scenarios 3 and 4 as defined in Chapter 5. This calculation is based on the method described in the Appendix of Good Practice Guide 388 – Combined Heat and Power in Buildings (Action Energy, 2004). In determining installation, maintenance and running costs, several assumptions have been made and are included in Appendix D.

6.1.1 Results of the Life Cycle Cost Calculation

The approximate installation cost of a Trigeneration facility with 1 MW heating and electrical capacity and 700 kW cooling capacity is £887,834, see Table 7. This is 5.8 times the cost of an equivalent conventional boiler and chiller facility. These costs exclude pipework, valves, controls, flues, labour and all other associated costs to provide an operational facility. These additional costs are considered to be approximately equal for both Trigeneration and conventional facilities.

For this load ratio and utilisation, the annual running costs were found to be 34% greater for a conventional facility than for a Trigeneration facility. This can be attributed to the current unit price of electricity being three times that of gas. The payback period is estimated as follows:

Payback period (years) = Additional installation cost (£) / Annual running cost savings (£)

= (£887,834 – £153,013) / (£474,145 - £353,828)

= **6.1 years**

It is noted that this is the predicted minimum payback period of a Trigeneration facility, as it assumes the efficiency of the CHP engine is 87% (the highest efficiency of the all examined case studies), with the best performing heat to power ratio (1:1) and with a high proportion of heating compared with cooling output (3:1). The most cost effective installations reviewed in Chapter 4, showed payback periods of 7 to 8 years and this is likely to be more realistic.

It should be noted that the whole life cycle cost calculation below, neither considers any available grants and incentives for CHP, nor the full maintenance costs, only the additional maintenance cost for Trigeneration over conventional plant. It also does not consider the costs of a buried heating and cooling network, which may be required for some sites.

<table>
<tr><th colspan="2">Item</th><th>Installation Cost</th><th>Running Hours</th><th>Seasonal Efficiency/ COP</th><th>Required Output MWh/year</th><th>Input MWh/ year</th><th>Fuel Input</th><th>Fuel cost (£/MWh)</th><th>Annual Running Cost</th></tr>
<tr><td colspan="10">Conventional Plant Installation</td></tr>
<tr><td colspan="2">1 MW Gas fired Condensing Boiler</td><td>£29,257</td><td>4189</td><td>0.96</td><td>4189</td><td>4363</td><td>Gas</td><td>£23</td><td>£98,741</td></tr>
<tr><td colspan="2">700kW Water cooled Chiller</td><td>£76,575</td><td>1396</td><td>5.5</td><td>977</td><td>178</td><td>Elec</td><td>£71</td><td>£12,599</td></tr>
<tr><td colspan="2">700 kW Dry Air cooler capacity with inverter driven fans</td><td>£47,181</td><td>1396</td><td>-</td><td>-</td><td>49</td><td>Elec</td><td>£71</td><td>£3,465</td></tr>
<tr><td colspan="2">Grid Supply Electricity (£70.9/MWh)</td><td>£0</td><td>5585</td><td></td><td>5068</td><td></td><td>Elec</td><td>£71</td><td>£359,340</td></tr>
<tr><td colspan="2">Total</td><td>£153,013</td><td></td><td></td><td></td><td></td><td></td><td></td><td>£474,145</td></tr>
<tr><td colspan="10">Trigeneration Installation</td></tr>
<tr><td rowspan="2">Gas fired CHP engine</td><td>1 MW Heat</td><td rowspan="2">£687,197</td><td>4189</td><td>0.435</td><td>4189</td><td rowspan="3">14266</td><td rowspan="3">Gas</td><td rowspan="3">£23</td><td rowspan="3">£322,832</td></tr>
<tr><td>1 MW Electricity</td><td>5585</td><td>0.435</td><td>5166</td></tr>
<tr><td colspan="2">700 kW hot water fired absorption chiller</td><td>£106,275</td><td>1396</td><td>0.7</td><td>977</td></tr>
<tr><td colspan="2">1400 kW Dry Air cooler capacity with inverter driven fans</td><td>£94,362</td><td>1396</td><td>-</td><td>-</td><td>98</td><td>Elec</td><td>-</td><td>Note 1</td></tr>
<tr><td colspan="2">Additional Maintenance cost (0.6p/kWh electrical)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>£30,996</td></tr>
<tr><td colspan="2">Total</td><td>£887,834</td><td></td><td></td><td></td><td></td><td></td><td></td><td>£353,828</td></tr>
<tr><td colspan="10">Notes:
1. The electrical energy input for heat rejection, has been added to the required electrical output of the CHP engine.</td></tr>
</table>

Table 7 : Installation and Running Costs of a highly Efficient Conventional and Trigeneration Facility

Trigeneration Facility Whole Life Costing:

Whole Life Cost = Installation cost + est. plant life * (Annual running + maintenance costs)

= £887,834 + 20years * £353,828 = **£7.96 million**

Conventional Facility Whole Life Costing:

Whole Life Cost = Installation cost + est. plant life * (Annual running + maintenance costs)

= £153,013 + 20years * £474,145 = **£9.64 million**

Over an assumed plant life of 20 years, savings of £1.67 million could be realised based on current energy prices. Future trends in relative electricity and gas prices will affect the cost effectiveness of Trigeneration, as CHP reduces a site's grid electrical demand and increases its gas demand.

In the past year, BERR have reported non-domestic average gas prices rose by 32%, whereas electricity prices rose by only 9% (BERR, 2008). If this trend continues it will reduce the cost effectiveness of CHP and increase payback periods.

6.2 Financial Incentives for Trigeneration

The CHP Quality Assurance Programme defines what can be described as 'Good CHP', and it is a function of: 'Threshold Power Efficiency Criterion' and 'Threshold Quality Index Criterion'. The target criterion for each CHP scheme is different and is dependant upon the type, efficiency and heat to power ratio of the installation. The following financial benefits are available for 'Good CHP' schemes (Action Energy, 2004):

- Climate Change Levy (CCL) exemption – good quality schemes may be exempt from the climate change levy, which is placed on top of fuel prices and currently amounts to an average of 4.3%, depending on the consumer size (BERR, 2008).
- Enhanced Capital Allowances (ECAs) – provide a tax incentive for energy efficient technologies, which can save around 7-8% of the capital cost, over the product life.

Due to time constraints the above benefits and any other additional benefits available are not considered in this analysis.

6.3 Chapter Summary

Whole life costing of an efficient 1 MW electrical Trigeneration facility has shown savings of up to £1.67million over more conventional boiler and chiller plant are possible, over a 20 year plant life. A payback period of 6.1 years is also possible but based on the case studies reviewed, 7 to 8 years is more realistic. Government funded financial incentives are also available for 'good quality' CHP schemes, which would further reduce payback periods.

The above savings are however only possible if the annual heat utilisation is above 90%, i.e. there is minimal dumping of excess generated heat. The heat to power ratio must also be low, preferably 1:1 and the heating to cooling ratio should ideally be 3:1 or greater. The relative trends in gas and electricity prices will also affect the success of a Trigeneration scheme. Over the past year gas prices have risen more steeply than electricity prices and this is reducing the cost effectiveness of Trigeneration. One of the reasons operation at the Met Office Trigeneration facility was suspended was because of this rise in gas prices relative to electricity prices.

The following chapter examines the potential for the wide spread introduction of Trigeneration in the UK and outlines some of the key issues surrounding it, which would need to be addressed.

7 Trigeneration Potential for the UK

The previous chapters have shown that Trigeneration can offer both environmental and financial savings over conventional plant. This chapter examines other issues surrounding Trigeneration which may affect its feasibility and also estimates the potential UK carbon emissions savings achievable with mass implementation of Trigeneration.

7.1 Decentralised Energy and District Heating and Cooling

The following outlines some of these key issues associated with decentralised energy:

- To provide a significant proportion of the UK's electrical energy from decentralised power plants would require several thousand CHP and CCHP installations in UK towns and cities. The largest facility analysed was the Citigen Ltd installation, which, provides 44 GWh of electrical output. To achieve only 10% of the UK's electrical output of 394,447 GWh, 897 equivalent facilities would be required.
- Each Trigeneration facility would require constant monitoring by qualified facilities management staff and engineers, to ensure efficient delivery of electricity and high reliability of supply.
- The gas supply infrastructure would require a significant upgrade to deliver gas to each of these sites. With large power plants gradually decommissioned, demand for coal, oil and nuclear fuel would decrease, whilst the demand for gas would increase. The electricity infrastructure would also require upgrading where sites are designed to export surplus electricity to the grid.
- Each of these CHP installations will require large flues, taller than the surrounding building, to ensure exhaust fumes don't enter adjacent buildings. These flues are likely to be an unpopular addition to city and town skylines and obtaining planning permission for these facilities is likely to be difficult.
- The local generation of electricity would also increase carbon dioxide, nitrous oxide and sulphur emissions within towns and cities, reducing the air quality in these urban and often already highly polluted areas.
- There could also be distribution losses of up to 2% with decentralised electricity generation and distribution, depending upon the size of the installation and area served (Thronger J., 2007), partially offsetting the carbon savings.

In addition to the issues associated with decentralised energy, there are several key problems associated with district heating and cooling.

- To provide efficient energy delivery, careful sizing of each system would be required to ensure there is sufficient year round heating and cooling demand and that the installed CHP capacity is appropriate for the base heating load. This may be difficult if the energy demand of the district is unstable or unpredictable.
- Installing buried district heating and cooling mains adds significant cost, due to the required civil works and the resulting disruption to roads. Ideally pipes would be installed above ground, to reduce installation cost and future maintenance costs. do not agree
- Utilicom, who have over 40 years experience in district heating and CHP in Europe, have estimated that district cooling is 50-100% more expensive to install and operate than a district heating scheme of the same capacity. Larger pipes and additional pumping energy is required, as the smaller flow and return temperature difference of chilled water, at 8°C compared with 30 °C difference for heating water, requires 3.8 times the flow rate to achieve the same output. It is, therefore, only considered cost effective for core buildings near to the facility to be connected to the district cooling network.
- District heating is often quoted of producing losses of up to 10% compared with decentralised heat generation (Thronger J., 2007). Typically, connection to individual consumers on each scheme is via a plate heat exchanger, which has inherent inefficiencies further lowering the efficiency of delivered energy.
- Convincing customers to connect to the schemes may be challenging and in order for the schemes to be financially viable, most of the sites adjacent to each plant would need to be supplied by it. The Southampton Trigeneration scheme has reported difficulties in attracting customers, which would make the scheme more cost effective. In Denmark, where district heating is wide spread in urban areas, legislation had to be changed to force people to give up there own boilers and connect to district heating schemes, to make the schemes viable (Sonne P., 2008).
- In Denmark, it was found that only areas with a heat consumption density greater than 30 MW/km² are environmentally and financially appropriate for district heating (Sonne P., 2008). Due to the time constraints of this study, it was not possible to determine what this figure would be for the UK and what percentage of buildings are located in these areas.

7.2 The Potential Carbon Emissions Savings of Trigeneration

UK Energy Usage by End Sector (GWh)		
Sector	**Gas Usage 2006**	**Elec Usage 2006**
Domestic	364,555	116,449
Industry Use	143,766	116,305
Public Administration	48,853	21,994
Commercial	34,279	75,376
Other	20,079	0
Agriculture	2,013	4,130
Transport	0	8,527
Total:	**613,545**	**342,781**
Emissions (Tonnes $C0^2$)	126,390,270	178,897,404
Total Emissions (Tonnes $C0^2$)	**305,287,674**	

Table 8 : UK Energy Usage and Carbon Emissions by End Sector (BERR, 2007)

Table 8 indicates the total UK gas and electrical energy consumption by end user group, this totals 956,000 GWh. The carbon emissions associated with this, based on 2006 carbon emission factors, is 305 million tonnes of carbon dioxide.

The following is an indicative calculation which estimates the likely maximum potential carbon dioxide savings from Trigeneration in the UK. It was not possible to undertake this calculation with a high degree of accuracy, as the efficiency and hence feasibility of each individual CCHP installation is dependant on many factors such as heat density of networks and load profiles. The London Climate Change agency has a target decentralised electrical energy proportion for London of 50% by 2050 (Jones, A, 2007). For the purposes of this calculation, it is assumed that 50% of all delivered electricity in the UK could be from CCHP. It is assumed that it would not be cost effective or efficient to deliver a greater proportion of UK energy than this, as many of the buildings within the UK are in rural locations or in areas of low building density.

The analysis in chapter 5 has shown that as the ratio of cooling to heating increases in CCHP installations, overall carbon emissions rates also increase, the same is true for the ratio of heat to power. The least carbon intensive Trigeneration facilities are those which have a heat to power ratio of 1 to 1 and where the cooling proportion is small, preferably less than a third of the heating output, hence these figure will be used for the calculation.

The following additional assumptions have been made:

- 50% of electricity, plus an equal combined quantity of heating and cooling energy can be supplied from decentralised CCHP facilities. It is noted that further analysis would be needed to confirm whether this is feasible.
- The assumptions regarding carbon content of fuel and efficiency of conventional and Trigeneration facilities are as per those stated in Chapter 5.

7.2.1 Calculated Emissions with CCHP Generating 50% of the UK's Electricity

The calculation in Table 9 compares the carbon emissions of Scenarios 1 and 4, as defined in Chapter 5, i.e. typical existing conventional plant installations and highly efficient Trigeneration facilities.

Potential UK Carbon emissions Reduction with Trigeneration (Comparing Scenario 1 and Scenario 4)
UK Gas consumption = 613,545 GWh 50% electricity from UK power station = 171,391 GWh 50% electricity from CCHP = 171,391 GWh
Heating energy from CCHP CCHP Heat to Power Ratio 1:1, 75% of heat used for heating purposes and 25% for cooling purposes. = 128,543 GWh heating energy + 42,848 GWh heat to be used to generate cooling
Cooling Energy from CCHP = Heat supplied to Absorption chiller * Efficiency of Absorption Chiller = 42,848 * 0.7 = 29,993 GWh cooling
Reduced electrical usage due to absorption cooling = Cooling output / COP of typical conventional chiller = 29,993 / 3.4 = 8,822 GWh
Gas input to generate 171,391 GWh electricity and 171,391 GWh heat energy = total output / CCHP efficiency = (171,391 + 171,391) / 0.87 = 394,001 GWh

Increased gas usage due to CCHP = CCHP Gas input – Useful Heat Output that would otherwise be generated in a gas boiler Where; (Useful CCHP Heating Output) = CCHP Gas input * (efficiency of heat generation in CCHP engine/efficiency of heat generated in a typical conventional boiler) = 394,001 – (171,391 *(43.5 % / 80.0 %)) = 300,808 GWh
Total Carbon emissions Carbon Emissions = Energy usage * carbon emissions factor By Power Stations = (171,391 - 8,822) GWh * 521.9 = 84,844,761 tonnes CO_2 From Gas Consumption = (613,545 +300,808) GWh * 206 = 188,356,718 tonnes CO_2 Total = 84,844,761 + 188,356,718 = **273,201,479 tonnes CO_2**
Reduced CO_2 emissions over conventional plant: Reduced emissions = Actual carbon emissions – predicted emissions with Trigeneration 305,287,674 - 273,201,479 = **32,086,195 tonnes CO_2 or 10.5 %**

Table 9 : Potential UK Carbon emissions Reduction with Trigeneration

The analysis suggests a reduction of up to 10.5 % of UK carbon emissions attributed to gas and electricity consumption is possible, though installing Trigeneration facilities to meet 50% of the United Kingdom's electrical demand and an equal combined quantity of heating and cooling energy. This is a significant reduction, which would be a large step towards meeting the government's 60% carbon dioxide reduction target for 2050.

The above calculation was repeated to compare Scenarios 1 and 2, plus Scenarios 3 and 4, as defined in Chapter 5. These calculations are included within Appendix D and are summarised on the following page.

Figure 21 illustrates the predicted total UK carbon dioxide emissions for delivered gas and electricity, for various Trigeneration and conventional plant scenarios. Typical performing Trigeneration facilities offer only minor carbon emissions savings (1.5%) over typical conventional plant, whereas highly efficient facilities can offer savings of 10.5%. The reduction possible if 50% of existing power stations were replaced with modern highly efficient CCGT power stations and conventional plant installation upgraded to highly efficient equivalents, is similar to that possible through installing highly efficient CCHP installations to meet 50% of the UK's electrical annual energy demand. However, a carbon emissions reduction of 16.5 % is possible if all UK power station are upgraded to highly efficient CCGT power stations and all conventional boiler and chiller plant installations upgraded to highly efficient modern equivalents.

It is noted that 4,485 CCHP installations of similar capacity to the Citigen installation would be required to meet 50% of the UK's annual electrical energy demand. Whereas there are only 66 main fossil fuelled power stations in the UK, which are not combined-cycle gas turbine stations (BERR, 2007).

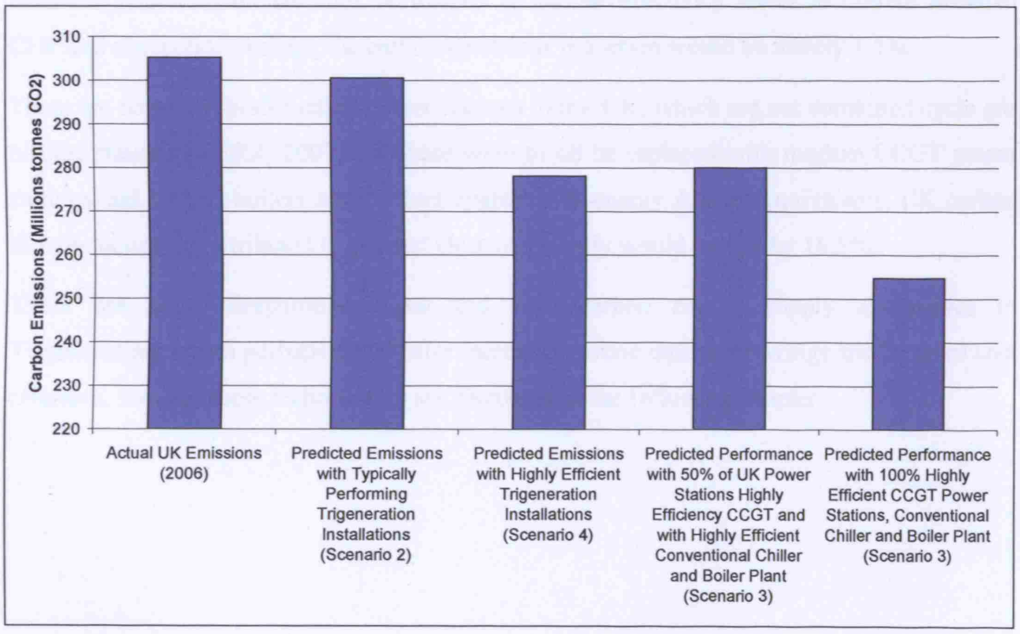


Figure 21: Predicted UK Carbon Dioxide Emissions

7.3 Chapter Summary

It would require a detailed study of the whole of the UK to determine exactly what percentage of delivered electricity could be met cost effectively and efficiently by Trigeneration. In Denmark, it was found that it was appropriate only where the heat density is greater $30MW/km^2$ and legislation had to be changed to force people to connect to local networks, to ensure their cost effectiveness. For the purposes of this study it has been assumed 50% of delivered electricity could potentially be from Trigeneration facilities, this is the 2050 government target for London.

If 50% of UK electricity could be delivered from highly efficient CCHP installations, carbon emissions reductions for delivered UK gas and electrical energy of up to 10.5% could be realised. Approximately 4,485 CCHP installations, of similar capacity to the Citigen installation, would be required to meet 50% of the UK's annual electrical energy demand. All these installations would have to be in close proximity to densely populated areas, to ensure the district heating and cooling networks were cost effective. Each of these installations would require at least one large flue, taller than the surrounding buildings, which may be unpopular with neighbouring residents and planners and would increase local. If newly installed Trigeneration facilities performed at similar efficiency levels to current installed CHP and absorption chillers, the carbon emissions reduction would be merely 1.5%.

There are 66 main fossil fuelled power stations in the UK, which are not combined cycle gas turbine stations (BERR, 2007). If these were to all be replaced with modern CCGT power stations and all UK boilers and chillers upgraded to energy A-rated equivalents, UK carbon dioxide emissions attributed to gas and electrical supply would reduce by 16.5%.

There are many decentralised low and zero carbon energy supply alternatives to Trigeneration, which perhaps could offer increased carbon emission savings and be more cost effective, some of these technologies are discussed in the following chapter.

8 Low Carbon Alternatives to Trigeneration

As well as trigeneration, many other decentralised non-conventional electrical, heating and cooling generation technologies exist which could potentially provide carbon savings over traditional grid supply, conventional boiler and chiller plant. The advantages and disadvantages of many of these are briefly summarised in Table 10.

n-nuclear tidal

Technology	Installation Cost[1]	Advantages[2]	Disadvantages[2]
Wind Turbines	£1000/kW	Excess electricity can be sold to the grid, gives a building an easily identifiable green image and requires no fuel input.	Not generally suited to dense urban environments, as there are usually insufficient wind speeds available at low level to generate a significant portion of a buildings load and flat sharp edged high rise buildings do not suit roof mounted turbines.
Solar Thermal Panels	£400/m^2	Relatively inexpensive, can meet a high proportion of a sites domestic hot water needs and requires no fuel input.	Only suitable for generating domestic hot water and so the overall proportion of a building's energy load which can be met is typically low, except in housing, leisure and catering premises.
Photovoltaics	£850/kW	Silent, with low maintenance requirements due to no moving parts and requires no fuel input.	Expensive, inefficient, and requires a large roof or façade area for mounting, if a significant portion of a site's load is to be met. Not always compatible with architectural styles.
Biomass Boilers	£200/kW	Setup costs relatively inexpensive and output is not affected by external climate conditions.	Often requires backup boilers due to associated maintenance issues. Requires large plant and fuel storage area, regular delivery of fuel to site and ash removal. Emissions issues may make obtaining planning permissions difficult.
Ground Source Heating and Cooling	£800/kW	Relatively efficient, requires no external mounting of plant. Output is not dependent on external climatic conditions.	Expensive, not all ground types suitable.

Notes:
[1] Cost data taken from London Renewables Toolkit (Faber Maunsell, 2004)
[2] Qualitative information based on that highlighted in the London Renewables Toolkit (Faber Maunsell, 2004) and Renewables and the London Plan (Irwin, G. 2007).

Table 10 : Summary of Decentralised Low Carbon Energy Supply Alternatives to Trigeneration

8.1 Chapter Summary

Wind turbines, solar thermal panels and photovoltaics deliver electrical and heating energy without any carbon emissions, however, unlike Trigeneration, output is dependent on solar intensity or wind speed and direction, which is both unpredictable and varies seasonally. It can therefore be difficult and expensive to obtain a high proportion of a site's energy requirements from these renewable sources. Biomass boilers, although relatively inexpensive to install, require fuel input to generate heating energy and hence have a higher operational cost than other renewable technologies. Biomass delivery can also be impractical in dense towns and cities and to reduce the frequency of fuel delivery, large biomass stores are needed.

Providing the ground conditions are suitable, ground source heating and cooling can provide a significant proportion of a buildings energy load, irrespective of the external climatic conditions and without the need to deliver a solid fuel to site.

Due to the constraints of this study, there was insufficient time to compare the predicted carbon and financial performance of the above mentioned technologies with Trigeneration. It is, however, believed that because of the reasons discussed, that of those technologies mentioned, only ground source heating and cooling could perhaps rival Trigeneration, in providing significant carbon emissions reductions in the UK.

9 Conclusions

Within this study the potential for Trigeneration in the UK has been examined and comparisons made with typical and highly efficient conventional installations with grid electrical supply, gas condensing boilers and mechanical vapour compression chillers. To evaluate the potential and likely success of mass implementation of Trigeneration, the following was undertaken:

- Six existing case studies were reviewed in detail and the Trigeneration facility at the Natural History Museum was visited and the former resident engineer interviewed.
- A study examining the theoretical global warming impact of Trigeneration compared with modern conventional plant, in various scenarios, was undertaken. This includes calculation of carbon dioxide emissions for different load scenarios and the contribution of refrigerants to global warming. Water consumption and noise from Trigeneration facilities was also examined.
- The whole life cost of a highly efficient 1 MW CHP engine and 700 kW absorption chiller was predicted and compared to that of an equivalent modern highly efficient conventional grid supply, boiler and chiller plant installation.
- The potential for wide spread usage of Trigeneration was discussed, including analysis of non-environmental and financial items obtained from the questionnaire results and literature review. The reduction in UK carbon emissions possible if 50% of the delivered electricity in the UK were supplied by decentralised Trigeneration facilities was predicted.
- Low and zero carbon decentralised energy supply alternatives to Trigeneration were briefly discussed.

Research showed four of the six Trigeneration installations examined can be considered a success in terms reliability, financial and environmental benefits. Of the remaining two, one was a pilot scheme and operation at the other was suspended due to a high rise in gas price relative to grid electricity price, reducing the cost effectiveness of decentralised electrical generation. Of the six case studies examined, all those serving existing buildings claim carbon savings over the previous electrical grid supply system, boiler and chiller plant installations. However, the installations were typically replacing 50 year old boiler and aging chiller plant with modern units and so carbon savings would be expected.

Calculation results have shown carbon emissions per GWh output from a Trigeneration facility can be as much as 34% less than those emitted from typical conventional plant and 10% less than modern efficient conventional plant. It was found that using the Building Regulations method for determining carbon emissions in buildings, greatly over-exaggerates the carbon savings possible with Trigeneration. This is likely to encourage CCHP schemes, as the relatively onerous Building Regulations emission targets can be difficult to achieve.

Although absorption chillers use refrigerants with a zero global warming potential, the global warming impact of fluorinated refrigerants used in conventional chillers, was found to be negligible in comparison with the carbon emissions generated by chillers, in the production of chilled water for cooling purposes. Plant noise is increased with Trigeneration installations, due to the added noise of the CHP engine but this is relatively easily mitigated if the plant is located in a noise sensitive area, through installing the CHP engine within an acoustic enclosure and with careful positioning of the flue. Water consumption is reduced with Trigeneration, providing the proportion of electrical output exceeds that of the cooling output.

Whole life costing of an efficient 1 MW Trigeneration facility has shown savings of up to £1.67million are possible over a 20 year plant life, compared with more conventional boiler and chiller plant. A payback period of 6.1 years is also possible but based on the case studies reviewed, 7 to 8 years is more realistic. Government funded financial incentives are also available for 'good quality' CHP schemes, which would further reduce payback periods.

The stated carbon emissions and financial savings are however only possible if the annual heat utilisation is above 90%, i.e. there is minimal dumping of generated heat. The heat to power ratio must also be low, preferably 1:1 and the heating to cooling ratio should ideally be 3:1 or greater.

In Denmark, it was found that CHP was appropriate only where the heat density is greater 30MW/km^2 and legislation had to be changed to force people to connect to local networks, to ensure cost effectiveness. It would require a detailed study of the heat density of the whole of the UK to determine exactly what percentage of delivered electricity could be met cost effectively and efficiently by Trigeneration. For the purposes of this study an indicative figure of 50% of delivered electricity in the UK from Trigeneration facilities, has been assumed to be economically and environmentally feasible.

If 50% of UK electricity could be delivered from highly efficient CCHP installations, carbon emissions reduction for delivered UK gas and electrical energy of up to 10.5% could be realised. Approximately 4,485 CCHP installations, of similar capacity to the Citigen installation, would be required to meet 50% of the UK's annual electrical energy demand. Each of these installations would require at least one large flue, taller than the surrounding buildings, which may be unpopular with neighbouring residents and planners and would increase local emissions.

A Trigeneration facility has greater spatial requirements than conventional plant, which may influence feasibility in refurbishments and in new builds where plant space is limited. This is because absorption chillers are 2.5 times the size of conventional chillers and require twice the heat rejection plant and CHP engines require more space than conventional boilers. For example the 1.9MW thermal installation at the Natural History requires the same plant space as a 12.5 MW boiler in the same plantroom.

Due to the constraints of this study, there was insufficient time to compare the predicted carbon and financial performance of other available low and zero carbon technologies with Trigeneration. It is, however, believed that based on the reasons discussed in Chapter 8, only ground source heating and cooling could perhaps rival Trigeneration, in providing significant carbon emissions reductions in the UK.

Overall, providing that Trigeneration is sized correctly, it has the potential to offer significant environmental benefits and financial savings over typical conventional facilities, currently installed across the UK. Trigeneration is feasible for mass implementation within the UK and we are likely to see an increase in the number of Trigeneration facilities because of local government decentralised energy targets and the relatively onerous carbon emissions target of the Building Regulations.

Despite the clear benefits of CCHP, it is difficult to predict whether we will move our energy needs towards a Trigeneration solution. There are many hindrances to its introduction including the high installation cost, disturbance associated with installing CCHP facilities and heating and cooling networks and whether consumers would be willing to abandon their own boilers and chillers and connect to local networks.

An alternative solution to reduce UK carbon emissions attributed to delivered energy, with fewer disturbances to the utilities networks, is to replace the 66 existing inefficient fossil fuelled power stations, with modern efficient combined cycle gas turbine power stations. As aging boiler and chiller plant is refurbished, it should also be replaced with modern highly efficient conventional equivalents. The long term result of this would be a 6% greater carbon emission reduction, than is envisaged possible with mass implementation of Trigeneration.

For this reason, this study shows widespread installation of CCHP is not the best means currently available to lower carbon emissions attributed to energy generation and assist in meeting the UK's 2050 target to reduce emissions by 60%. Trigeneration is, however, a beneficial and feasible short term alternative to reduce the UK's impact on Global Warming.

9.1 Recommendations

- In the short term consider Trigeneration for all site's with a high base heating load, such as new housing schemes, hotels, hospitals, mixed-use developments, leisure centres and museums. CHP engines should be sized with a heat to power ratio of 1:1 and heating to cooling output ratio should be 3:1 or greater.
- Adopt a long term strategy to replace the 66 existing inefficient fossil fuelled power stations with modern CCGT power stations.

9.2 Future Uncertainties

The following future uncertainties should be considered, as they may invalidate the conclusions of this feasibility study and hence the appropriateness of the recommendations.

- Future trends in coal, gas and grid electricity prices could both increase or decrease the cost effectiveness of Trigeneration in comparison with conventional plant.
- As new more efficient power stations replace aging ones, the carbon emissions per GWh will decline. This will reduce the emissions factor for grid electricity and will favour conventional plant installations.
- As developments continue in alternative low and zero carbon technologies, the performance and appropriateness of another energy source may overshadow that of Trigeneration.
- As older buildings are replaced by newer air tight and better insulated units, heating loads are likely to decrease and perhaps cooling loads may increase. Because Trigeneration is more efficient at delivering heating energy rather than cooling energy, this could reduce its appropriateness.
- Future changes in environmental legislation might further reduce permitted carbon emissions in buildings and hence may force designers to adopt non-conventional energy supply methods such as Trigeneration to meet carbon emissions targets.

9.3 Further Work

The following items are suggested topics of further work, which would be of additional benefit in the evaluation of Trigeneration for the UK market:

- The advantages and disadvantages of incorporating thermal storage within a combined, cooling, heating and power installation.
- Sizing Trigeneration facilities for various building types e.g. housing, educational and office developments, to determine the percentage of load which can be met in a low carbon intensive and cost effective manner.
- Environmental and financial analysis of district heating and cooling, compared with decentralised energy supply systems.
- The effect of decentralised electricity generation on air quality in towns and cities.
- Financial and environmental comparisons of Trigeneration with fuel cells, ground source heating and cooling.
- Analysis of adsorption chillers and whether these offer any benefits over absorption chillers.

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Appendix A – Trigeneration Questionnaire

Tri-generation (Combined Cooling, Heating and Power) Questionnaire

Environmental Design and Engineering MSc Dissertation

Ashley Stone- May 2008

This questionnaire forms part of a study carried for my MSc in Environmental Design and Engineering, at the Bartlett Graduate School of UCL.

The aim of the questionnaire is to provide me with data to assist with my MSc dissertation, in which I hope to evaluate the feasibility of combined cooling, heating and power within the United Kingdom. This study is focusing on CHP with connected absorption chiller.

If you are able to assist I would be extremely grateful if you could fill in this questionnaire or if you could send it to any persons you believe can help. The success of this dissertation is greatly dependant on my ability to obtain relevant and accurate results and there are only a handful of existing installations in the UK.

If you wish for your answers to remain anonymous, I will not include your name or the project details within my report.

I would be grateful if you could fill in **one** questionnaire for **each** Tri-generation job you have been involved on.

Name (please leave blank if you wish to remain anonymous):

Site name and location:

1. **What is your involvement in the design/installation/operation of this Tri-generation plant?** (e.g. design engineer, facility manager etc...)

2. **For the above mentioned site, please list the building/development type?** e.g. office, retail, hospital, industrial, mixed-use etc...

3. **Main reasons for choosing Tri-generation:**
(Number main reasons in order i.e. 1 = most important reason, 2 = second most important reason etc...)

To increase green credentials		Pressure from planning control	
To meet BREEAM, Part L or local government low carbon targets		Government grant or other financial incentive	
For long term financial savings		Other (please state)	
Client preference			

4. **Make and model of the installed Tri-generation equipment:**

5. **Rated output of the Tri-generation facility:**

Rated electrical output		kW
Rated heating output		kW
Rated cooling output		kW

6. **Does the installation sell electricity back to the grid in periods of low electrical demand and high heating or cooling demand?**

Yes or No	

7. **Does the installation incorporate chilled water or heating hot water thermal storage?**

Yes or No	

8. **Actual Annual Input and Output from the Tri-Generation Installation:**
(If available, full hourly data for the installed period would be extremely useful)

	Year 1 (kWh)	Year 2 (kWh)	Year 3 (kWh)
Gas Input			
Electrical Input			
Actual electrical annual output			
Actual heating annual output			
Actual cooling annual output			

9. **What approximate percentage of the total building load is met by Tri-Generation?** (E.g. 50% electricity from Tri-Generation, 50% from the grid)

Electrical annual output		%
Heating annual output		%
Cooling annual output		%

10. **Total Project Fee**

£

11. **Tri-generation/CCHP installation cost**

£

12. **Estimated payback period**

______Years

13. **Overall how would you rate the reliability of the plant:**

Very reliable	
Reasonably reliable	
Unreliable	

14. If known can you please comment on the running and maintenance costs of operating the Tri-generation facility, compared to a traditional boiler and chiller installation with grid-connected electricity. (If known the number of maintenance hours spent each month and cost of maintenance, would be extremely useful)

15. What is your general opinion of the tri-generation plant:

Very impressed with it	
Generally pleased with it	
OK	
A little disappointed	
Very disappointed	

16. Overall what would you say were the main <u>positive</u> aspects of Tri-generation?

17. Overall what would you say were the main <u>negative</u> aspects of Tri-generation?

Many thanks for taking the time to fill in the above questionnaire, if you have any questions regarding this study please do not hesitate to contact me. If requested the results of this study can be sent to you.

I would be extremely grateful if you could forward this form to any other persons which you believe may be able to assist me in my analysis of Tri-generation.

Appendix B - Summary of Case Studies

The Natural History Museum, London

Summary of Natural History Museum Trigeneration Facility (Information Obtained from Questionnaire Response and CIBSE Presentation - Jan 2008)	
Contact:	Simon Tilleard
Role:	Conceived Project and was Project Director, working for the Museum.
Site:	Museum with office accommodation, storage, laboratories and galleries.
Reasons for incorporating Trigeneration:	Long term financial savings and to increase green credentials.
Make and Model of Installed Plant	Bespoke GE Jenbacher reciprocating CHP plant and Thermax single-effect hot water fired absorption Chillers.
Rated Output	1.82 MWe - electrical 1.9 MWth – heating 1.5 MWc - cooling
Grid Connection	No, not required as demand exceeds supply.
Thermal Storage	No, not required as demand almost always exceeds supply.
Energy Input & Useful Output	Gas Input: 26,000 MWh Electrical Output: 10,500 MWh Heating Output: 8,500 MWh Cooling Output: 2,500 MWh Net Efficiency: (10,500+8,500+2500) / 26,000 = 82.7 %* *Ignores electrical input associated with heat rejection from absorption chillers.
Proportion of the Site Load Met	Electrical: 30% Heating: Unknown Cooling: 60%
Total Project Fee	NA
Trigeneration Installation Cost	£3.7 million
Estimated Payback Period:	7.8 years
Reliability	Very reliable
Running and Maintenance Costs	Comparable with conventional plant.
Overall Opinion	Very Impressed with the installation.
Positive Aspects	The excellent carbon emissions efficiency is excellent and it encourages overall site operations to improve efficiency and design to maximise the benefits of the trigeneration plant
Negative Aspects	You lose cooling when the plant shuts down. If this is critical it can be an issue unless contingency plans are in place.

Citigen Ltd, London

Summary of Citigen (Information Obtained from Questionnaire Response and CIBSE Presentation - May 2006)	
Contact:	John Bradshaw
Role:	Production Coordinator
Site:	Large Mixed-Use
Reasons for incorporating Trigeneration:	Large scale CHP initiative in north London, designed to be a flagship scheme for replica in other cities.
Make and Model of Installed Plant	2 * Wartsila 18V46 duel fuel diesels (Plus 3 * gas fired Wellman Robey Euronox Conventional Boilers) 2* Trane Absorption Chillers (Plus 3 * Carrier Vapour Compression Chillers)
Rated Output	31.6 MWe - electrical 25 MWth – heating 11.2 (Absorption) + 4.2 (Electric) MWc – cooling
Grid Connection	Yes
Thermal Storage	No
Energy Input & Useful Output	Gas Input: 158 GWh Electrical Output: 44 GWh Heating Output: 44 GWh Cooling Output: 23 GWh Net Efficiency: (44+44+23) / 158 = 70.2 %* *Ignores electrical plant consumption, which is quoted as 2 MW or 6% of electricity produced. Site efficiency up until now has varied from 50 – 70% depending on heating demand.
Proportion of the Site Load Met	100%
Total Project Fee	NA
Trigeneration Installation Cost	£80 million
Estimated Payback Period:	Unknown but site currently operates at a loss
Reliability	Reasonably reliable
Running and Maintenance Costs	Citigen has traditionally operated at a substantial loss, however there is substantial opportunity for future expansion and with plant improvements, it is hoped the plant will turn to profit. This plant has had a troubled history not helped by multiple changes in ownership.
Overall Opinion	The problems of Citigen are down to a troubled ownership history and some poor equipment and installation, not the concept itself.
Positive Aspects	District heating and electrical supply from this type of urban tri-gen plant offers a very energy efficient solution to urban energy demand and should be a major part of future energy planning in the UK, similar schemes operate very successfully in other countries
Negative Aspects	The scheme is currently uneconomical, at times heat for absorption chillers coming from the boilers rather than CHP. Absorption chillers don't respond to load variations very well, resulting in flow temperature fluctuations.

West Quay, Southampton

Summary of Southampton Scheme (Information obtained from Questionnaire Response and Presentation May 2006)	
Contact:	Craig Grobety / Simon Woodward
Role:	Energy Technician at Utilicom, designers, installers and operators of the CCHP facility.
Site:	Mixed-use.
Reasons for incorporating Trigeneration:	Long term financial savings, to increase green credentials and was the Client's preference.
Make and Model of Installed Plant	Wartsila CHP with absorption chiller.
Rated Output	6.43 MWe – electrical 31.1 MWth – heating 9.3 MWc – cooling
Grid Connection	Yes
Thermal Storage	Yes
Energy Input & Useful Output	2007: Gas Input: 67,000 MWh Electrical Input: 2,400 MWh Electrical Output: 15,800 MWh Heating Output: 31,300 MWh Cooling Output: 5,300 MWh Net Efficiency: (15,800-2,400+31,300+5,300) / 67,000 = 74.6 % 2006: Gas Input: 63,300 MWh Electrical Input: 2,600 MWh Electrical Output: 9,200 MWh Heating Output: 34,500 MWh Cooling Output: 6,400 MWh Net Efficiency: (9,200-2,600+34,500+6,400) / 63,300 = 75 % 2005: Gas Input: 89,800 MWh Electrical Input: 523 MWh Electrical Output: 24,400 MWh Heating Output: 33,600 MWh Cooling Output: 6,200 MWh Net Efficiency: (24,400-523+33,600+6,200) / 89,000 = 71.6 %
Proportion of the Site Load Met	Electrical: 0% - 100% sold to grid Heating: 100% Cooling: 100%
Total Project Fee	NA
Trigeneration Installation Cost	£4 million
Estimated Payback Period:	8 years
Reliability	Reasonably reliable
Running and Maintenance Costs	No comment.
Overall Opinion	Generally pleased with the installation.
Positive Aspects	Seasonal operation and Load consistency.
Negative Aspects	District cooling networks are expensive to install due to the small difference in flow and return temperatures compared with district heating (more pumping energy). Struggled to attract additional consumers which would make the scheme more financially viable.

The Met Office, Exeter

Summary of Met Office Trigeneration Facility (Information Obtained from CIBSE Presentation - May 2006)	
Presenter:	Julian Packer
Role:	Director – Cogenco (CHP Supply, Operation and Maintenance Firm)
Site:	Office.
Reasons for incorporating Trigeneration:	Unknown.
Make and Model of Installed Plant	Cogenco – Cummins QSV91 CHP engine with Thermax LT31S absorption chiller.
Rated Output	1.5 MWe – electrical 1.69 MWth – heating 1.0 MWc – cooling
Grid Connection	No
Thermal Storage	No
Energy Input & Useful Output	Unknown But claims to provide a 21% reduction in energy and Carbon Dioxide.
Proportion of the Site Load Met	Electrical: Portion Heating: Portion Cooling: 100% - Sized to meet cooling load
Total Project Fee	Unknown
Trigeneration Installation Cost	Unknown
Estimated Payback Period:	Unknown
Reliability	Operation suspended after nearly two years in operation, due to adverse spark spread.
Running and Maintenance Costs	Unknown.
Overall Opinion	Unknown.
Positive Aspects	Carbon savings possible over conventional plant, depending on carbon factor used.
Negative Aspects	Operation had to be suspended and there is a risk of crystallisation if prolonged shutdown.

George Square, University of Edinburgh

Summary of University of Edinburgh Trigeneration Facility (Information Obtained from CIBSE Presentation - May 2006 and Correspondence with David Baratt)	
Presenter:	David Barratt
Role:	Engineering Operations Manager, University of Edinburgh
Site:	Multiple buildings at University of Edinburgh
Reasons for incorporating Trigeneration:	Unknown.
Make and Model of Installed Plant	GE Jenbacher 612 CHP engine with absorption chiller.
Rated Output	1.6 MWe – electrical 1.7 MWth – heating 0.6 MWc – cooling
Grid Connection	Unknown.
Thermal Storage	Yes, 75 cubic metres.
Energy Input & Useful Output	2007: Gas Input: 27.9 GWh Electrical Output: 10.2 GWh Heating Output: 8.7 GWh Cooling Output: 0.42 GWh Net Efficiency: (10.2+8.7+0.42) / 27.9 = 69.2%* *Ignores electrical input associated with heat rejection from chillers. Claims carbon savings of up to 1,254 tonnes each year.
Proportion of the Site Load Met	Electrical: 67 % Heating: 74 % Cooling: 100 %
Total Project Fee	£6.9 million (£2.7 million community energy grant obtained)
Trigeneration Installation Cost	£1.6 million
Estimated Payback Period:	Less than 7 years
Reliability	Very reliable
Running and Maintenance Costs	O&M contract based on hours of operation. Comprehensive maintenance service with guaranteed availability.
Overall Opinion	This is the third CHP scheme at Edinburgh university, all of which are considered a success.
Positive Aspects	Improvements in energy efficiency and reductions in carbon emissions.
Negative Aspects	Increased maintenance costs and control requirements.

Royal Mail, Slough

Summary of Royal Mail Trigeneration Facility (Information Obtained from CIBSE Presentation - January 2008)	
Presenter:	Alan Barlow
Role:	Managing Director, ENER.G Combined Power (Designers, constructers and operators of the plant)
Site:	50,000m^2 Royal Mail Group facility, mix of sorting machinery and offices
Reasons for incorporating Trigeneration:	Green credentials.
Make and Model of Installed Plant	ENER.G 1000 CHP engines with LG LWM – K027 absorption chillers.
Rated Output	3.0 MWe – electrical 3.5 MWth – heating 1.4 MWc – cooling (plus 3.6 MW from Mechanical Vapour Compression chillers)
Grid Connection	No.
Thermal Storage	No.
Energy Input & Useful Output	Unknown but reported to be 74% efficient.
Proportion of the Site Load Met	Electrical: 100 % Heating: 100 % Cooling: Unknown %
Total Project Fee	Unknown
Trigeneration Installation Cost	£6 million
Estimated Payback Period:	Unknown
Reliability	Unknown but CHP plant availability was listed as 95%+ and absorption chillers 99%+. The facility was installed with conventional boilers, chillers and generators to provide 100% redundancy.
Running and Maintenance Costs	Unknown but a team of four staff run the energy centre on rotation.
Overall Opinion	Positive, performed as intended.
Positive Aspects	Good plant efficiency, environmental and financial running cost savings. Good security of supply, with facility to increase capacity in the future.
Negative Aspects	Very expensive installation costs, due to need to provide 100% redundancy for heating, cooling and electrical energy.

Appendix C1 – Calculated carbon Emissions Results Based on Actual Published Data

The following calculation assumptions were made in determining the carbon emissions of conventional and trigeneration facilities:

- The efficiency of delivered electricity is taken as 41%, which is the published BERR figure for the UK in 2006. Distribution losses have been taken as 7.5% as this is also the published BERR figure.
- The efficiency of a modern Combined Cycle Gas Turbine has been taken as 55%, this is the efficiency of Coolkeeragh, which as of 2006, was the most efficient CCGT in the UK and was completed in 2005.
- The seasonal efficiency of a modern boiler has been taken as 96%, as this is the minimum required value to obtain an A-rating for energy efficiency.
- The typical efficiency of a boiler installation in the UK is taken as 80% because this is the minimum permitted value within the Building Regulations 2006 for refurbishments and so is assumed to be a good depiction of a typical installed UK boiler.
- The seasonal energy efficiency ratio of a modern mechanical vapour compression chiller has been taken as 5.5, as this is the minimum required value to obtain an A-rating for energy efficiency. This excludes energy input for heat rejection.
- The typical Seasonal energy efficiency rating of a water cooled mechanical vapour compression chiller installation in the UK is taken as 3.4 because this is the minimum permitted value within the Building Regulations 2006 and so is assumed to be a good depiction of an average installed UK water cooled chiller. This excludes energy input for heat rejection.
- The seasonal energy efficiency rating of an absorption chiller is taken as 0.7, which is the typical maximum efficiency of a single effect hot water fired chiller used in a Trigeneration facility. This excludes energy input for heat rejection.
- Ancillary power for heat rejection from mechanical vapour compression chillers is taken as 50 KWh electrical per MWh cooling and 100 kWh electrical per MWh cooling with an absorption chiller (Woods P., 2008).
- The efficiency of a typical CHP facility is taken as 67.7%, which is the BERR published average net efficiency of all the major installed facilities in the UK in 2006.

- The efficiency of a high performing CHP facility is taken as 87%, which is the highest efficiency of the reviewed case studies i.e. the Natural History Museum.
- Various heat to power ratios from 1:1 to 4:1, were examined to see their effect on carbon emissions.
- Two ratios of heating and cooling output were examined; 75% heating with 25% cooling and 50% heating with 50% cooling, to see the effect on carbon emissions.

Calculation Assumptions Summary	
Item	**Efficiency**
Typical Power Station	0.41
Modern CCGT Power Station	0.55
Modern Boiler	0.96
Typical Boiler	0.8
Modern chiller (COP)	5.5
Typical Chiller (COP)	3.4
Typical Trigeneration Overall Efficiency	0.677
Modern Trigeneration Overall Efficiency	0.87
Electrical Distribution Loss Factor	1.075
Heat Rejection / MWh	**Energy Input**
Conventional Chiller Heat Rejection Energy	50 KWh
Absorption Chiller Heat Rejection Energy	100 KWh
Carbon Factor	**KG CO_2/kWh**
Actual Gas Emissions factor 2006	0.206
Actual Average Grid Electrical Emissions factor 2006 inc distribution losses	0.5219
Building Regulations Gas Emissions factor	0.194
Building Regulations Grid Electrical Emissions factor inc distribution losses	0.422
Building Regulations Grid Electrical Emissions displacement factor	0.568

Summary Table - Carbon Emissions in Thousand tonnes per GWh					
Heat/Cooling Ratio	Heat to Power Ratio	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
75% Heat 25% cooling	1	0.383	0.324	0.281	0.252
	1.5	0.356	0.328	0.262	0.256
	2	0.338	0.331	0.249	0.258
	3	0.315	0.334	0.233	0.260
	4	0.301	0.336	0.224	0.262
50% Heat 50% cooling	1	0.378	0.344	0.266	0.268
	1.5	0.350	0.353	0.245	0.274
	2	0.331	0.358	0.230	0.279
	3	0.307	0.365	0.212	0.284
	4	0.293	0.369	0.202	0.287

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 1:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8	62.2	36.4	48.4
Heating	15	18.8		15.6	
Cooling	5	1.5		0.9	
Heat rejection plant input	-	0.6	0.7	0.5	0.6
Energy Input	40	69.6	63.0	53.4	49.0
Overall Efficiency		**57.5**	**63.5**	**75.0**	**81.6**
Carbon Emissions (thousand tonnes CO_2)		15.3	13.0	11.2	10.1
Carbon Emissions (thousand tonnes CO_2/GWH)		0.38	0.32	0.28	0.25

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 1:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8	65.4	36.4	50.9
Heating	10	12.5		10.4	
Cooling	10	2.9		1.8	
Heat rejection plant input	-	1.2	1.5	0.9	1.1
Energy Input	40	65.4	66.9	49.5	52.1
Overall Efficiency		**61.1**	**59.8**	**80.8**	**76.8**
Carbon Emissions (thousand tonnes CO_2)		15.1	13.8	10.7	10.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.38	0.34	0.27	0.27

Carbon Performance of Trigeneration and Conventional Plant (Heat to Power Ratio - 1.5:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	78.6	36.4	61.2
Heating	22.5	28.1		23.4	
Cooling	7.5	2.2		1.4	
Heat rejection plant input	-	0.9	1.1	0.7	0.9
Energy Input	50	80.0	79.7	61.8	62.0
Overall Efficiency		**62.5**	**62.7**	**80.8**	**80.6**
Carbon Emissions (thousand tonnes CO_2)		17.8	16.4	13.1	12.8
Carbon Emissions (thousand tonnes CO_2/GWH)		0.36	0.33	0.26	0.26

Carbon Performance of Trigeneration and Conventional Plant – (Heat to Power Ratio - 1.5:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	83.4	36.4	64.9
Heating	15	18.8		15.6	
Cooling	15	4.4		2.7	
Heat rejection plant input	-	1.8	2.2	1.4	1.7
Energy Input	50	73.8	85.6	56.1	66.6
Overall Efficiency		**67.8**	**58.4**	**89.2**	**75.1**
Carbon Emissions (thousand tonnes CO_2)		17.5	17.6	12.2	13.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.35	0.35	0.24	0.27

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 2:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8	95.0	36.4	73.9
Heating	30	37.5		31.3	
Cooling	10	2.9		1.8	
Heat rejection plant input	-	1.2	1.5	0.9	1.1
Energy Input	60	90.4	96.4	70.3	75.0
Overall Efficiency		**66.3**	**62.2**	**85.3**	**80.0**
Carbon Emissions (thousand tonnes CO_2)		20.3	19.9	14.9	15.5
Carbon Emissions (thousand tonnes CO_2/GWH)		0.34	0.33	0.25	0.26

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 2:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8	101.3	36.4	78.8
Heating	20	25.0		20.8	
Cooling	20	5.9		3.6	
Heat rejection plant input	-	2.4	3.0	1.8	2.3
Energy Input	60	82.1	104.2	62.7	81.1
Overall Efficiency		**73.1**	**57.6**	**95.8**	**74.0**
Carbon Emissions (thousand tonnes CO_2)		19.8	21.5	13.8	16.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.33	0.36	0.23	0.28

Carbon Performance of Trigeneration and Conventional Plant – (Heat to Power Ratio - 3:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	127.7	36.4	99.3
Heating	45	56.3		46.9	
Cooling	15	4.4		2.7	
Heat rejection plant input	-	1.8	2.2	1.4	1.7
Energy Input	80	111.3	129.9	87.3	101.1
Overall Efficiency		**71.9**	**61.6**	**91.6**	**79.2**
Carbon Emissions (thousand tonnes CO_2)		25.2	26.8	18.7	20.8
Carbon Emissions (thousand tonnes CO_2/GWH)		0.32	0.33	0.23	0.26

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 3:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	137.2	36.4	106.7
Heating	30	37.5		31.3	
Cooling	30	8.8		5.5	
Heat rejection plant input	-	3.7	4.4	2.7	3.4
Energy Input	80	98.8	141.6	75.8	110.2
Overall Efficiency		**81.0**	**56.5**	**105.5**	**72.6**
Carbon Emissions (thousand tonnes CO_2)		24.6	29.2	17.0	22.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.31	0.36	0.21	0.28

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 4:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	160.4	36.4	124.8
Heating	60	75.0		62.5	
Cooling	20	5.9		3.6	
Heat rejection plant input	-	2.4	3.0	1.8	2.3
Energy Input	100	132.1	163.3	104.3	127.1
Overall Efficiency		**75.7**	**61.2**	**95.9**	**78.7**
Carbon Emissions (thousand tonnes CO_2)		30.1	33.6	22.4	26.2
Carbon Emissions (thousand tonnes CO_2/GWH)		0.30	0.34	0.22	0.26

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 4:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	173.0	36.4	134.6
Heating	40	50.0		41.7	
Cooling	40	11.8		7.3	
Heat rejection plant input	-	4.9	5.9	3.6	4.6
Energy Input	100	115.4	178.9	88.9	139.2
Overall Efficiency		**86.6**	**55.9**	**112.4**	**71.8**
Carbon Emissions (thousand tonnes CO_2)		29.3	36.9	20.2	28.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.29	0.37	0.20	0.29

Appendix C2 – Calculated Carbon Emissions Results Based on Building Regulation Carbon Factors

Calculation Assumptions Summary	
Item	**Efficiency**
Typical Power Station	0.41
Modern CCGT Power Station	0.55
Modern Boiler	0.96
Typical Boiler	0.8
Modern Chiller (COP)	5.5
Typical Chiller (COP)	3.4
Typical Trigeneration Overall Efficiency	0.677
Modern Trigeneration Overall Efficiency	0.87
Electrical Distribution losses	1.075
Heat Rejection / MWh	**Energy Input**
Conventional Chiller Heat Rejection Energy	50 KWh
Absorption Chiller Heat Rejection Energy	100 KWh
Carbon Factor	**KG CO_2/kWh**
Actual Gas Emissions factor 2006	0.206
Actual Average Grid Electrical Emissions factor 2006 inc distribution losses	0.5219
Building Regulations Gas Emissions factor	0.194
Building Regulations Grid Electrical Emissions factor inc distribution losses	0.422
Building Regulations Grid Electrical Emissions displacement factor	0.568

Summary Table - Carbon Emissions in Thousand tonnes per GWh					
Heat/Cooling Ratio	**Heat to Power Ratio**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
75% Heat 25% cooling	1	0.324	0.023	0.301	-0.046
	1.5	0.304	0.084	0.277	0.013
	2	0.291	0.124	0.261	0.053
	3	0.275	0.175	0.241	0.103
	4	0.265	0.175	0.241	0.103
50% Heat 50% cooling	1	0.316	0.043	0.290	-0.032
	1.5	0.294	0.108	0.264	0.031
	2	0.280	0.152	0.246	0.073
	3	0.262	0.206	0.224	0.125
	4	0.252	0.238	0.211	0.157

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 1:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	62.6	36.4	48.4
Heating	15	18.8		15.6	
Cooling	5	1.5		0.9	
Heat rejection plant input	-	0.6	0.7	0.5	0.6
Energy Input	40	69.6	63.3	53.4	49.0
Overall Efficiency		**57.5**	**63.2**	**75.0**	**81.6**
Carbon Emissions (thousand tonnes CO_2)		13.0	0.9	12.0	-1.9
Carbon Emissions (thousand tonnes CO_2/GWH)		0.32	0.02	0.30	-0.05

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 1:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	66.0	36.4	50.9
Heating	10	12.5		10.4	
Cooling	10	2.9		1.8	
Heat rejection plant input	-	1.2	1.5	0.9	1.1
Energy Input	40	65.4	67.5	49.5	52.1
Overall Efficiency		**61.1**	**59.2**	**80.8**	**76.8**
Carbon Emissions (thousand tonnes CO_2)		12.6	1.7	11.6	-1.3
Carbon Emissions (thousand tonnes CO_2/GWH)		0.32	0.04	0.29	-0.03

Carbon Performance of Trigeneration and Conventional Plant (Heat to Power Ratio - 1.5:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8	79.1	36.4	61.2
Heating	22.5	28.1		23.4	
Cooling	7.5	2.2		1.4	
Heat rejection plant input	-	0.9	1.1	0.7	0.9
Energy Input	50	80.0	80.2	61.8	62.0
Overall Efficiency		**62.5**	**62.4**	**80.8**	**80.6**
Carbon Emissions (thousand tonnes CO_2)		15.2	4.2	13.9	0.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.30	0.08	0.28	0.01

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 1.5:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8	84.3	36.4	64.9
Heating	15	18.8		15.6	
Cooling	15	4.4		2.7	
Heat rejection plant input	-	1.8	2.2	1.4	1.7
Energy Input	50	73.8	86.5	56.1	66.6
Overall Efficiency		**67.8**	**57.8**	**89.2**	**75.1**
Carbon Emissions (thousand tonnes CO_2)		14.7	5.4	13.2	1.6
Carbon Emissions (thousand tonnes CO_2/GWH)		0.29	0.11	0.26	0.03

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 2:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	95.6	36.4	73.9
Heating	30	37.5		31.3	
Cooling	10	2.9		1.8	
Heat rejection plant input	-	1.2	1.5	0.9	1.1
Energy Input	60	90.4	97.1	70.3	75.0
Overall Efficiency		**66.3**	**61.8**	**85.3**	**80.0**
Carbon Emissions (thousand tonnes CO_2)		17.5	7.5	15.7	3.2
Carbon Emissions (thousand tonnes CO_2/GWH)		0.29	0.12	0.26	0.05

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 2:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	Required Output (GWh)	Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency	Scenario 2: Typical CHP and Absorption Chiller Performance in 2006	Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller	Scenario 4: Efficient Trigeneration Facility
Electricity	20	48.8	102.5	36.4	78.8
Heating	20	25.0		20.8	
Cooling	20	5.9		3.6	
Heat rejection plant input	-	2.4	3.0	1.8	2.3
Energy Input	60	82.1	105.5	62.7	81.1
Overall Efficiency		**73.1**	**56.9**	**95.8**	**74.0**
Carbon Emissions (thousand tonnes CO_2)		16.8	9.1	14.8	4.4
Carbon Emissions (thousand tonnes CO_2/GWH)		0.28	0.15	0.25	0.07

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 3:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8		36.4	
Heating	45	56.3	128.6	46.9	99.3
Cooling	15	4.4		2.7	
Heat rejection plant input	-	1.8	2.2	1.4	1.7
Energy Input	80	111.3	130.8	87.3	101.1
Overall Efficiency		**71.9**	**61.2**	**91.6**	**79.2**
Carbon Emissions (thousand tonnes CO_2)		22.0	14.0	19.3	8.2
Carbon Emissions (thousand tonnes CO_2/GWH)		0.27	0.18	0.24	0.10

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 3:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8		36.4	
Heating	30	37.5	139.0	31.3	106.7
Cooling	30	8.8		5.5	
Heat rejection plant input	-	3.7	4.4	2.7	3.4
Energy Input	80	98.8	143.5	75.8	110.2
Overall Efficiency		**71.9**	**61.2**	**91.6**	**79.2**
Carbon Emissions (thousand tonnes CO_2)		21.0	16.5	18.0	10.0
Carbon Emissions (thousand tonnes CO_2/GWH)		0.26	0.21	0.22	0.13

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 4:1 - 75% heat / 25% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8		36.4	
Heating	60	75.0	161.6	62.5	124.8
Cooling	20	5.9		3.6	
Heat rejection plant input	-	2.4	3.0	1.8	2.3
Energy Input	100	132.1	164.6	104.3	127.1
Overall Efficiency		**75.7**	**60.8**	**95.9**	**78.7**
Carbon Emissions (thousand tonnes CO_2)		26.5	20.6	22.9	13.3
Carbon Emissions (thousand tonnes CO_2/GWH)		0.27	0.21	0.23	0.13

Carbon Performance of Trigeneration and Conventional Plant - (Heat to Power Ratio - 4:1 - 50% heat / 50% cooling energy)					
		Energy Input to achieve Required Output (GWh)			
Energy	**Required Output (GWh)**	**Scenario 1: Conventional Grid Electrical Supply, with typical boiler and Chiller Efficiency**	**Scenario 2: Typical CHP and Absorption Chiller Performance in 2006**	**Scenario 3: Modern Efficient Power Station, Condensing Boiler and Conventional Chiller**	**Scenario 4: Efficient Trigeneration Facility**
Electricity	20	48.8		36.4	
Heating	40	50.0	175.5	41.7	134.6
Cooling	40	11.8		7.3	
Heat rejection plant input	-	4.9	5.9	3.6	4.6
Energy Input	100	115.4	181.4	88.9	139.2
Overall Efficiency		**86.6**	**55.1**	**112.4**	**71.8**
Carbon Emissions (thousand tonnes CO_2)		25.2	23.8	21.1	15.7
Carbon Emissions (thousand tonnes CO_2/GWH)		0.25	0.24	0.21	0.16

Appendix D – Whole Life Costing Analysis

The following assumptions have been taken for the whole life costing analysis calculations in Chapter 6:

- The seasonal efficiency of a modern boiler has been taken as 96%, as this is the minimum required value to obtain an A-rating for energy efficiency.
- The seasonal energy efficiency ratio of a modern mechanical vapour compression chiller has been taken as 5.5, as this is the minimum required value to obtain an A-rating for energy efficiency. This excludes energy input for heat rejection.
- The seasonal energy efficiency rating of an absorption chiller is taken as 0.7, which is the typical maximum efficiency of a single effect hot water fired chiller used in a Trigeneration facility. This excludes energy input for heat rejection.
- Ancillary power for heat rejection from mechanical vapour compression chillers is taken as 50 KWh electrical per MWh cooling and 100 kWh electrical per MWh cooling with an absorption chiller (Woods P., 2008).
- The efficiency of a high performing CHP facility is taken as 87%, which is the highest efficiency of the reviewed case studies i.e. the Natural History Museum.
- A heat to power ratio of 1:1 is examined i.e. heat energy is generated with an efficiency of 43.5% and electricity is generated with an efficiency of 43.5%, within the CHP engine. This ratio is selected as it was found to be the most efficient for a trigeneration facility, out of those load scenarios examined in Chapter 5.
- The ratio of heating and cooling output was taken as 75% heating and 25% cooling. Again this was found to be the most efficient ratio examined in Chapter 5, for a trigeneration facility.
- Cost data for chillers, boilers, heat rejection plant and CHP engines has been taken from SPON'S Mechanical and Electrical Services Price Book 2006 (Langdon D., 2005).
- Maintenance costs are as per those suggested in Good Practice Guide 388 i.e. 0.6p/kWh greater for CHP (Action Energy, 2004).
- Energy Prices are taken as 2.263p/kWh gas and 7.09p/kWh electricity, this is the Department for Business Enterprise and Regulatory Reform published data for the first quarter of 2008, and excludes the climate change levy (BERR, 2008).

- Output is based on a 1 MW thermal/1 MW electrical CHP plant in operation for 5585 hours a year, as per the GPG 388 calculation, which is typical for a good quality CHP scheme.
- Heat utilisation is taken as 90%, the suggested figure in GPG 388 for a CHP scheme of this size is 84% but as this scheme incorporates an absorption chiller, it has been deemed heat utilisation will be greater.
- This calculation excludes any possible financial benefits available for low carbon technologies.

Appendix E – Predicted UK Carbon Emissions with Trigeneration

Potential UK Carbon Dioxide Emissions Reduction with Trigeneration (Comparing Scenario 1 and Scenario 2)
UK Gas consumption = 613,545 GWh 50% electricity from UK power station = 171,391 GWh 50% electricity from CCHP = 171,391 GWh
Heating energy from CCHP CCHP Heat to Power Ratio 1:1, 75% of heat used for heating purposes and 25% for cooling purposes. = 128,543 GWh heating energy + 42,848 GWh heat to be used to generate cooling
Cooling Energy from CCHP = Heat supplied to Absorption chiller * Efficiency of Absorption Chiller = 42,848 * 0.7 = 29,993 GWh cooling
Reduced electrical usage due to absorption cooling = Cooling output / COP of typical conventional chiller = 29,993 / 3.4 = 8,822 GWh
Gas input to generate 171,391 GWh electricity and 171,391 GWh heat energy = total output / CCHP efficiency = (171,391 + 171,391) / 0.677 = 506,323 GWh
Increased gas usage due to CCHP = CCHP Gas input – Useful Heat Output that would otherwise be generated in a gas boiler Where; (Useful CCHP Heating Output) = CCHP Gas input * (efficiency of heat generation in CCHP engine/efficiency of heat generated in a typical conventional boiler)

=506,323 – (171,391 *(33.9 %/80%)) = 433,804 GWh
Total Carbon Dioxide Emissions Carbon Emissions = Energy usage * carbon emissions factor By Power Stations = (171,391 - 8,822) GWh * 521.9 = 84,844,761 tonnes CO_2 From Gas Consumption = (613,545 +433,804) GWh * 206 = 215,753,869 tonnes CO_2 Total = 84,844,761 + 215,753,869 = **300,598,594 tonnes CO_2**
Reduced CO_2 emissions over conventional plant: Reduced emissions = Actual carbon emissions – predicted emissions with trigeneration 305,287,674 - 300,598,594 = **4,689,080 tonnes CO_2 or 1.5 %**

Potential UK Carbon Dioxide Emissions Reduction with Trigeneration (Comparing Scenario 3 and Scenario 4)
UK Gas consumption = 613,545 GWh 50% electricity from UK power station = 171,391 GWh 50% electricity from CCHP = 171,391 GWh
Heating energy from CCHP CCHP Heat to Power Ratio 1:1, 75% of heat used for heating purposes and 25% for cooling purposes. = 128,543 GWh heating energy + 42,848 GWh heat to be used to generate cooling
Cooling Energy from CCHP = Heat supplied to Absorption chiller * Efficiency of Absorption Chiller = 42,848 * 0.7 = 29,993 GWh cooling
Reduced electrical usage due to absorption cooling

= Cooling output / COP of typical conventional chiller = 29,993 / 5.5 = 5,453 GWh
Gas input to generate 171,391 GWh electricity and 171,391 GWh heat energy = total output / CCHP efficiency = (171,391 + 171,391) / 0.87 = 394,001 GWh
Increased gas usage due to CCHP = CCHP Gas input – Useful Heat Output that would otherwise be generated in a gas boiler Where; (Useful CCHP Heating Output) = CCHP Gas input * (efficiency of heat generation in CCHP engine/efficiency of heat generated in a typical conventional boiler) = 394,001 GWh – (171,391 *(43.5%/96%)) = 316,340 GWh
Total Carbon Dioxide Emissions Carbon Emissions = Energy usage * carbon emissions factor By Power Stations = (171,391 - 5,453) GWh * 521.9 = 86,602,606 tonnes CO_2 From Gas Consumption = (613,545 +316,340) GWh * 206 = 191,556,275 tonnes CO_2 Total = 86,602,606 + 191,556,275 = **278,158,882 tonnes CO_2**
Reduced CO_2 emissions over conventional plant: Reduced emissions = Actual carbon emissions – predicted emissions with trigeneration Where actual carbon emissions = (electrical energy generated * emissions factor) + (gas consumption * emissions factor) = (342,781 * (206/55%)) + (613,545 * 206) = 254,777,335 254,777,335 - 278,158,882 = **- 23,381,546 tonnes CO_2 or - 9.2 %**